Weather Avoidance Using Route Optimization as a Decision Aid: An AWIN Topical Study

W-04
035003

Phase I Report
December 30, 1998

Prepared for:
NASA Langley Research Center
Under Cooperative Agreement No. NCC-1-291
Technical Officer: Kara Latorella
Grant Administrator: C. Lynn Jenkins

Prepared by:
Honeywell Technology Center
3660 Technology Drive
Minneapolis, MN 55408

1.0 Executive Summary

The aviation community is faced with reducing the fatal aircraft accident rate by 80 percent within 10 years. This must be achieved even with ever increasing traffic and a changing National Airspace System. This is not just an altruistic goal, but a real necessity, if our growing level of commerce is to continue.

Honeywell Technology Center's topical study, "Weather Avoidance Using Route Optimization as a Decision Aid", addresses these pressing needs. The goal of this program is to use route optimization and user interface technologies to develop a prototype decision aid for dispatchers and pilots. This decision aid will suggest possible diversions through single or multiple weather hazards and present weather information with a human-centered design. At the conclusion of the program, we will have a laptop prototype decision aid that will be used to demonstrate concepts to industry for integration into commercialized products for dispatchers and/or pilots.

With weather a factor in 30% of weather accidents, our program will prevent accident by strategically avoiding weather hazards in flight. By supplying more relevant weather information in a human-centered format along with the tools to generate flight plans around weather, aircraft exposure to weather hazards can be reduced. Our program directly addresses the NASA's five year investment areas of Strategic Weather Information and Weather Operations (simulation/hazard characterization and crew/dispatch/ATChazard monitoring, display, and decision support) (NASA Aeronautics Safety Investment Strategy: Weather Investment Recommendations, April 15, 1997).

This program is comprised of two phases. Phase I concluded December 31, 1998. This first phase defined weather data requirements, lateral routing algorithms, and conceptual displays for a user-centered design. Phase II runs from January 1999 through September 1999. The second phase integrates vertical routing into the lateral optimizer and combines the user interface into a prototype software testbed. Phase II concludes with a dispatcher and pilot evaluation of the route optimizer decision aid.

This document describes work completed in Phase I in contract with NASA Langley August 1998 – December 1998. The purpose of this document is to fulfill the following requirements from the responsibility agreement as stated under cooperative agreement number NCC-1-291 "Weather Avoidance Using Route Optimization as a Decision Aid":

Provide NASA with Phase I report. This report shall include:

- Discuss of how weather hazards were identified in partnership with experts, and how weather hazards were prioritized
- Static representations of display layouts for integrated planning function
- Cost function for the 2D route optimizer
- Discussion of the method for obtaining, access to raw data of, and the results of the flight deck user information requirements definition (as detailed in subtask 2.1 of the proposal)
- Itemized display format requirements (as indicated in subtask 2.2 of the proposal) identified for representing weather hazards in a route planning aid.

This document accompanies a milestone 1 presentation and demo including delivery of object code of the route optimizer for laptop PC implementation.

2.0 Operational Concept

Flight planning is a complex task because of the number of dynamic world models it tries to encompass and optimize. Because the underlying models and assumptions made in an automated system may be incomplete and fallible, a "cooperative" rather than "automated" flight planner has been suggested (Layton 1994). A strategic planning and replanning flight optimization tool produces a flight plan that describes at what altitude, speed, and track an aircraft will fly during various flight phases. Ideally, this route determination is based upon several parameters including speed, fuel efficiency, passenger comfort, arrival time, air traffic congestion, favorable forecast weather (e.g., winds aloft), forecast weather hazards (e.g., turbulence, convection, icing, volcanic activity, ozone concentration), airport or runway closures, medical emergencies, overflight fees, etc. The goal of our program is to develop a tool for dispatchers and pilots that assists in the complex problem solving task of flight planning and replanning around weather hazards in a collaborative fashion where automation, dispatch, and pilots work towards an optimal solution while maintaining passenger comfort and flight safety.

2.1 Honeywell Technology Center Program

Honeywell would like to offer a product that could be used by dispatch, air traffic control, or pilots that would clearly identify the weather hazards and their potential impact on the safety of the flight. The route optimizer would optimize the route to avoid hazardous weather and allow the pilot a "What if?" scenario capability to evaluate operating costs, time costs, and safety costs.

Our approach uses both our human centered design expertise and route optimization technology to create such a decision aid. In partnership with weather experts, we created an integrated program with three strong domains. Figure 2.1 shows the three areas of our AWIN topical study to develop the route optimizer decision aid.

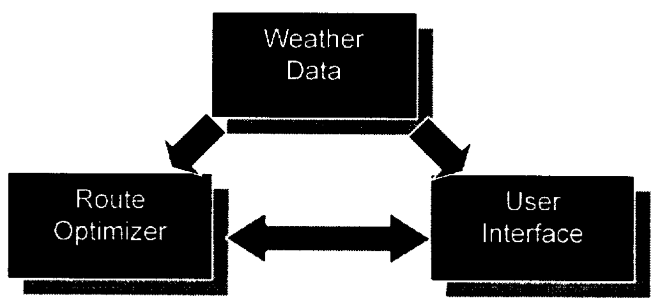


Figure 2.1. Three Components of AWIN Program

The first stage of our program involved visiting and interviewing experts in the field of weather. We visited a Flight Service Station, Kavouras, Northwest Airlines, and the National Center for Atmospheric Research (NCAR). We also interviewed a consulting weather expert, Wayne Sand, and a corporate pilot. We established the working environment of different stakeholders of weather routing and defined state-of-the-art weather products.

The second part of our program was to generate user requirements from our field visits and synthesize these requirements into conceptual display layouts. These display layouts are designed to integrate with the route optimizer in Phase II.

Finally, a portion of the program focused on developing an initial 2-D weather set for implementation in our route optimizer. We then developed and implemented algorithms for lateral routing using our 2-D weather set.

Each of the three areas of development; weather, route optimization, and user interface, are addressed below in detail.

2.2 Concept for Weather Avoidance

Creating a flight trajectory, especially a trajectory avoiding weather, is a complex task. A dispatcher or pilot must consider safety and at the same time consider factors that affect the individual flight plus the optimization of the entire fleet of aircraft. Through our visits and interviews, we compiled a list of factors that affect a user's decision making process when making routing decisions around weather. Figure 2.2 is a summary of these factors.

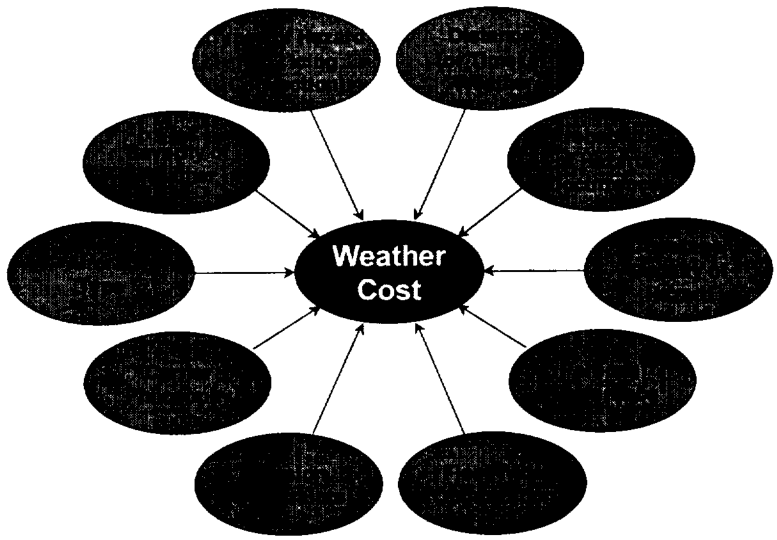


Figure 2.2. Factors Affecting Weather Routing Decisions

Flight optimization creates the "best" flight trajectory by minimizing the "cost" of multiple factors. Today, most flight planning systems optimize for factors fuel or time based on a "cost index" that converts both fuel and time into the same unit: money. For our program, we wanted to add weather to our optimizer as another factor to consider in our optimization. However, after multiple discussions, we established a concept of "fly and no-fly zones". Rather than try to put a hazard level and "danger index" into the optimizer (see section 5.0 for route optimization discussion), distinct zones would be defined as "fly" or "no fly" zones for the purposes of establishing a route. The benefits to creating a tool with clear, discrete fly or no fly zones are numerous. First, implementation into the route optimizer cost function is much clearer. There is no need to combine multiple factors into one "gain" in the cost function with no direct reference to weather hazard severity or other weighted classifications. Second, the route optimizer tool would behave in a predictable manner. The user can clearly visualize the routing "decisions" the route optimizer is making to avoid weather. Through direct manipulation of the weather hazard boundaries the user has concrete control over the behavior of the optimizer. Third, with visible boundaries around weather hazards, the standards for one flight can be applied to other flights. This allows for one standard to be used for multiple flights that would allow the user (most likely the dispatcher) to be able to understand the effects of the routing decision on the optimization of the fleet. Figure 2.3 below is a top-level diagram of the flow and function for the logic of weather avoidance routing decisions. In Phase II we will refine the process and algorithms for our user interface and route optimization algorithms.

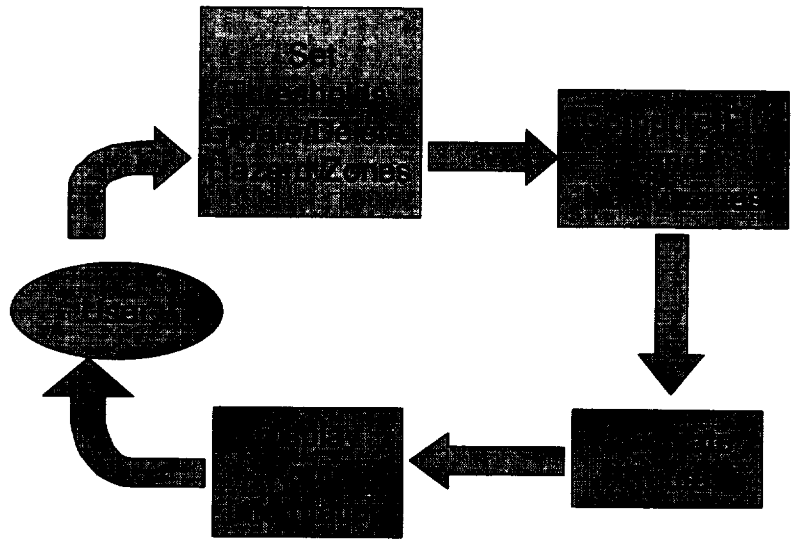


Figure 2.3. Operational Concept

3.0 Weather Hazards

In partnership with weather experts, we categorized and prioritized weather hazards for our topical area study. Our trip reports to various weather providers and users are summarized in Appendix B. First, we made some program assumptions, grouped weather hazards into five categories through interviews with weather users, and prioritized these categories for our program. Then we evaluated state-of –the-art weather products for the needs of our program.

3.1 Program Assumptions

The following are issues addressed by our program:

Strategic flight planning – Our route optimizer is currently designed as a "strategic" planner. The route optimizer uses a grid size that is proportional to the length of the flight. The current use of our grid size is not suited for high-resolution navigation. For instance, it would not be able to fly from coast to coast *and* pick its way through convective cells one mile in diameter. We will address a tactical problem in our human-in-the-loop evaluations to be sure that the route optimization decision tool will be used safely in a tactical situation, but for the rest of the program we will address only strategic issues.

International operations – Sources of available weather differ with location. Domestically, weather is available through multiple sources in the CONUS region. Internationally, especially in oceanic regions, much less weather information is available. We would like to address the weather needs for flight planning where less than the full complement of weather is available.

Forecasted weather data – Because our route planner is strategic, we need data that not only provides information on the current location of weather, but data that will also indicate where the weather will be in the future.

Integrated sensor data – It is vital to recognize that simply providing more weather information to operators won't adequately support effective decision making to deal safely with weather hazards. We want to support the use of a weather product that would integrate multiple sources of information such as radar, surface observations, satellite imagery, etc. to clearly define the location and severity of the weather hazards.

Enroute phase of flight – Different phases of flight encounter different weather hazards. For instance, microbursts greatly affect performance in lower altitudes and usually in the take-off or landing of an aircraft. Because our program in focusing on a strategic route planner, we decided to prioritize weather hazards that occur in the en route, or cruise, phase of flight.

3.2 Weather Hazard Categorization

In combination of literature review and speaking with field experts, the top 5 weather hazards were identified. We asked experts to list weather hazards to aircraft, leading with the most severe hazards first. The following table summarizes our interviews:

Wayne Sand	American Airlines	Northwest Airlines	NCAR
1. Thunderstorms	1. Turbulence	1. Convection	1. Convection
2. Turbulence	2. Icing	2. Snowstorm/Icing	2. Turbulence
3. Icing	3. Volcanic Ash	3. Turbulence	3. Icing
	4. Convective	4. Volcanic Ash	
		5. Ozone	

Table 3.1. Prioritization of Weather Hazards by Weather Experts

Although the relative importance of each hazard varies among operators, dependent upon operating philosophy and other factors (see Figure 2.2), they are generally categorized as:

- Convective Weather
- Icing
- Turbulence
- Volcanic Ash
- Ozone Concentration

This order of weather hazards also reflects the order of our approach for our program based on our research of state-of-the-art weather products.

3.3 Hazard Descriptions

After examining the priorities of each weather hazard, we examined how we can break down weather hazards into measurable factors to be used in the route optimizer. Here are general descriptions of each of the major hazards, the specific dangers aircraft face when encountering these hazards, and how these hazards are measured and described using intensity levels:

Convective Weather

Thunderstorms can contain some of the most dangerous weather elements including turbulence, hail, and icing. A recent incident in May 1998 involving a DC-9 operated by AirTran Airlines Inc. demonstrates what can happen when an aircraft tries to skirt too close to thunderstorm cells: hail shattered three front windshields, the radome was battered off the nose of the aircraft, and severe damage was inflicted to all leading edges, engine cowlings, and fans, necessitating an emergency landing. Turbulence associated with the encounter also resulted in two injuries, one of which was serious. (Accident Synopsis DCA98MA045 "Scheduled 14 CFR 121 operation of AirTran Airlines, INC" National Transportation and Safety Board Report, May 1998.) In addition to safety concerns, convective weather impacts air traffic delays. During the warm season, at least half of the national airspace system delays are caused by aircraft attempting to avoid thunderstorms (FAA Aviation Weather Research, **http://www.faa.gov/aua/awr/prodprog.htm**). Improvements in the ability to forecast convective weather coupled with the integration of this information in a flight planning tool that optimizes around the convective activity (or other hazard areas) will benefit users by increasing separation from convective weather and reducing air traffic delays by better planning before the aircraft is even airborne.

Some of the challenges in the routing around convective activity include attenuation, blocked or inoperative signals, lifetimes of cells, hazard being different from radar reflectivity, and transoceanic availability of relevant information. Attenuation of the signal, where the signal becomes weakened because it is absorbed, scattered, or reflected along its path, can make it difficult to see the targets in the background (e.g., in the air this means that cells behind the cell in front of you may not be displayed). The signal can also be blocked by mountainous terrain, or stations may simply become inoperative at various times. Because of the instability of convective activity, storms can mature and dissipate in less than an hour. Although radar returns are available every 5 minutes, the weather radar summary chart (with interpretations) is available only hourly from the NWS and the thunderstorm timeframe can be shorter than the time between hourly radar summary charts.

Currently, weather radar is the primary tool used to detect thunderstorms. The Next Generation Weather Radar system (NEXRAD) is capable of measuring winds out to 60nm and weather features to 130nm. A radar reflectivity intensity scale or VIP scale is used as an indication of precipitation rate. This scale is shown in the table below.

VIP Level	Precipitation Intensity	Rainfall Rate In/hr Stratiform	Rainfall Rate In/hr Convective
1	Weak	< 0.1	< 0.2
2	Moderate	0.1 – 0.5	0.2 – 1.1
3	Strong	0.5 – 1.0	1.1 – 2.2
4	Very strong	1.0 – 2.0	2.2 – 4.5
5	Intense	2.0 – 5.0	4.5 – 7.1
6	Extreme	> 5.0	> 7.1

Table 3.2. Video Integrator Processor (VIP) Intensity Levels for Liquid Precipitation (Adapted from FAA AC 00-45D)

Radar provides composite reflectivity data that are not necessarily consistent with the associated weather hazard phenomenon; a displaced gust front, hail, and severe turbulence may exist well outside the storm cloud. Additionally, radar is not available over the water so convective activity must be interpreted from satellite images.

Pilots will elect to fly through (and dispatcher will route through) an area of known convective activity if it is felt that they can "pick their way through it," i.e., perform lateral deviations around the individual cells. However, if the coverage is dense, they may elect to circumnavigate the whole area. The table below defines the commonly used terms in describing thunderstorm coverage.

Adjective	Coverage
Isolated	Single cells (no percentage)
Widely scattered	Less than 25% of area affected
Scattered	25 to 54% of area affected
Numerous	55% or more of area affected

Table 3.3. Area Coverage for Convection
(Adapted from FAA AC 00-45D)

In addition to coverage, an area of convective weather may be circumnavigated. Below is a chart defining the terms used to describe probability of convective activity occurring.

Term	Description
Occasional	Greater than 50% probability of the phenomenon occurring but for less than 1/2 of the forecast period
Chance	30 to 50% probability (precipitation only)
Slight Chance	10 to 20% probability (precipitation only)

Table 3.4. Variability Terms
(Adapted from FAA AC 00-45D)

Turbulence

Aircraft encounters with unexpected turbulence can be hazardous to the aircraft and passengers. For example, in 1997, there were 11 flight attendant injury reports and 6 passenger injury reports due to turbulence.

Turbulence, as reported by pilots, issued in SIGMETS, or convective SIGMETS, is reported as an intensity variable. Some levels of turbulence may be tolerable or acceptable when optimizing a flight plan. This of course depends upon the nature of the operation, e.g., cargo airlines may accept a higher level of tolerable turbulence to fly through than an airline concerned about passenger comfort and safety. However there is a level of turbulence that is unacceptable to fly through because it may cause structural damage and/or loss of flight control. The table below describes the turbulence intensity reporting descriptions along with associated effects on passengers and the aircraft.

Intensity	Aircraft Reaction	Reaction Inside Aircraft
Light	Turbulence that momentarily causes slight, erratic changes in altitude and/or attitude (pitch, roll, yaw). Report as *Light Turbulence.** **or** Turbulence that causes slight, rapid, and somewhat rhythmic bumpiness without appreciable changes in altitude or attitude. Report as *Light Chop.*	Occupants may feel a slight strain against belts or shoulder straps. Unsecured objects may be displaced slightly. Food service may be conducted and little or no difficulty is encountered in walking.
Moderate	Turbulence that is similar to Light Turbulence but of greater intensity. Changes in altitude and/or attitude occur but the aircraft remains in positive control at all times. It usually causes variations in indicated airspeed. Report as *Moderate Turbulence.** **or** Turbulence that is similar to Light Chop but of greater intensity. It causes rapid bumps or jolts without appreciable changes in aircraft altitude or attitude. Report as *Moderate Chop.*	Occupants feel definite strains against seat belts or shoulder straps. Unsecured objects are dislodged. Food service and walking are difficult.
Severe	Turbulence that causes large, abrupt changes in altitude and/or attitude. It usually causes large variations in indicated airspeed. Aircraft may be momentarily out of control. Report as *Severe Turbulence.**	Occupants are forced violently against seat belts or shoulder straps. Unsecured objects are tossed about. Food service and walking are impossible
Extreme	Turbulence in which the aircraft is violently tossed about and is practically impossible to control. It may cause structural damage. Report as Extreme Turbulence.*	
	* High level turbulence (normally about 15,000'AGL(that is not associated with cumuliform cloudiness, including thunderstorms, should be reported as CAT (clear air turbulence) preceded by the appropriate intensity,	
Reporting Term Definitions	Occasional – less than 1/3 of the time Intermittent – 1/3 to 2/3 of the time. Continuous – More than 2/3 of the time.	

Table 3.5. Turbulence Reporting Criteria (Adapted from FAA AC 00-45D)

Icing

The industry continues to confront icing as a major concern to aviation safety. In-flight icing is defined as "the accretion of supercooled liquid in clouds or precipitation onto an airframe during flight" (Politovich). Icing is a factor in numerous aircraft incidents and accidents. One notable accident involving the encounter of in-flight icing occurred in October 1994 when an Avions de Transport Regional ATR-72 operated by Simmons Airlines as American Eagle flight 4184 crashed after the flight crew lost control of the airplane during an adverse roll event at 9,200 feet. The crew of four and 64 passengers were killed and the airplane destroyed. The NTSB concluded that the loss of control was caused by a sudden and unexpected aileron hinge moment reversal that occurred after a ridge of ice built up beyond the deice boots.

Aircraft icing is a major hazard to aviation because of its potential to reduce aircraft efficiency, capability, power, and responsiveness. All field visits conducted including the FSS, Kavouras, Northwest AOC, and NCAR identified icing as a major aviation weather hazard. Icing is known as a cumulative hazard because it increases weight, reduces lift, decreases thrust, and increases drag simultaneously (AC 00 –6A). If the ice accumulates on the fuselage or wing, it can disrupt airflow and thus decrease the aircraft's flying capability. If the ice accumulates near an engine air intake, it can result in a loss of power. Icing can also build up on the brakes, landing gear, aft of wingboots, and other instruments or antenna, resulting in a hazardous situation (as it did in the ATR-72 accident previously mentioned).

Icing has the potential to form on an aircraft when it flies through visible moisture (i.e., rain droplets or clouds) *and* the temperature is at the point where the moisture striking the aircraft is 0°C or colder (Ahrens, 1988). The three types of aircraft icing have been classified as **clear**, **rime**, and **mixed**, and they have different effects on the aircraft. **Clear** ice can occur when an aircraft flies through an area of freezing rain (or in cumuliform clouds), and large supercooled drops strike the leading edge of the wing and form a thin film of water. This film of water quickly freezes and forms a smooth, solid, transparent sheet of ice. Clear ice can accumulate quickly and is most difficult for de-icing equipment to eliminate. **Rime** ice occurs when the cloud droplets freeze before they have time to spread, producing a rough, whitish brittle coat. It is lighter weight than clear ice and can be more easily removed by de-icers. The third type of icing in mixed. **Mixed** ice forms when drops are varied in size or when liquid drops are intermingled with ice particles or snow. In weather forecasts or PIREPS, icing is normally classified by type and intensity category. The following table describes the intensity levels along with associated operational effect on aircraft.

Intensity	Airframe Ice Accumulation
Trace	Ice* becomes perceptible. Rate of accumulation slightly greater than rate of sublimation. It is not hazardous even though deicing/ anti-icing equipment is not used unless encountered for an extended period of time (over one hour).
Light	The rate of accumulation may create a problem if flight is prolonged in this environment (over one hour). Occasional use of deicing/ anti-icing equipment removes/ prevents accumulation. It does not present a problem if the icing equipment is used.
Moderate	The rate of accumulation is such that even short encounters become potentially hazardous and use of deicing/ antiicing equipment or diversion is necessary.
Severe	The rate of accumulation is such that deicing/ anti-icing equipment fails to reduce or control the hazard. Immediate diversion is necessary.
	* Icing may be rime, clear and mixed.
Rime Ice:	Rough milky opaque ice formed by the instantaneous freezing of small supercooled water droplets
Clear Ice:	A glassy, clear or translucent ice formed by the relatively slow freezing of large supercooled water droplets.
Mixed Ice:	A combination of rime and clear ice

Table 4.0. Icing Intensities, and Airframe Ice Accumulation (Adapted from FAA AC 00-45D)

Volcanic Ash

When volcanoes erupt, they spew tons of ash particles into the atmosphere. These clouds spread downwind at an average of 600nm per day. As a pilot approaches an ash cloud, it is not always easy to distinguish them from "ordinary" clouds. For example, in December 1989, a Boeing 747-400, operated by KLM Royal Dutch Airlines as flight 867, lost all power and dropped from 25,000 to 12,000 feet in 12 minutes near Anchorage, Alaska. After 7-8 attempts to restart the engines, the crew successfully regained power. No injuries were reported, but there was extensive surface and engine damage in excess of $80 million to the aircraft. The NTSB ruled the incident an inadvertent encounter with a volcanic ash cloud. (Casadevall 1994 Hazards to aircraft flown through volcanic ash can be immediate or long term. Examples of immediate damage can include smoke and ash in the cockpit, windscreens unusable because of abrasion, and engine flameout. Long-term effects are more difficult to identify but may include damage to plastics, rubber seals, lubricants, and metal parts). Because of the immediate safety implications, the long-term hazardous effects, and the need to minimize disruption of schedules, the presence of airborne volcanic ash is an additional weather hazard that should be considered during route planning and replanning.

Ozone Concentration

Ozone is toxic to people and, when present in large concentrations, it can irritate the eyes and cause respiratory difficulties. Naturally occurring ozone in the stratosphere can create a hazard to flights. Usually, this higher concentration of ozone is above the altitudes that aircraft fly (with the exception of an super-sonic transport or some military aircraft). However, sometimes atmospheric conditions can draw the higher ozone concentration down to the lower altitudes where more aircraft fly. Some airlines restrict flights to lower altitudes when crossing a region of predicted ozone concentrations above a critical level. Therefore, for safety of passengers and crew, the presence of high ozone concentration is a weather hazard that should be considered during route planning and replanning.

4.0 Conceptual Display Layouts

Task 2 of Phase 1 was the formulation of the conceptual display layouts for the flight planning and replanning decision aid. Task 2 contained three parts: define dispatch/ flightcrew weather-related decisions and information requirements, determine display requirements for weather hazards, and develop conceptual display formats for integrated planning. To accomplish this goal, a user-centered requirements definition process was followed. First we learned how the tool would be used in an operational context by visiting with an FSS, Kavouras, NCAR, and NWA AOC. This helped us identify weather hazards that an aircraft would strategically route around, dispatcher responsibilities and tasks, and the determination of what information the operator would need to support decisions and tasks associated with strategic planning and replanning. The information support guidelines would drive the functionality and system requirements. Once the requirements had been formulated, conceptual static display concepts were generated. Figure 4.1 below shows the process followed in 1998 to generate display concepts.

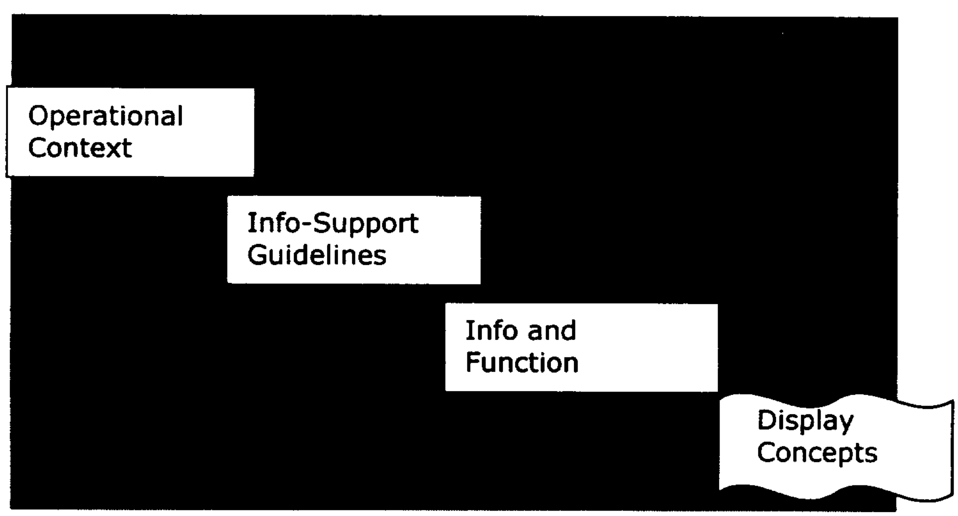


Figure 4.1. User-centered Design Process for Building Initial Display Concepts

4.1 Operational Context

An understanding of the operational context was developed through four on-sight visits, an interview with a pilot, and review of related literature. On our visits we met with and interviewed people at a Flight Service Station, aviation weather graphics provider, an AOC, and an experimental weather product development group. In addition, we informally interviewed airline and corporate pilots. We learned more about who the users are, what their responsibilities and tasks are, and what weather-related decisions they make. We learned more about the information that is required to support their tasks, what tools or products they currently use to do their job, and in what context the tool will be used. Table 4.1 below describes the parties that were visited and an overview of the nature of their operations. Appendix B contains the trip reports.

Job Title	Company	Nature of Operations
Weather Specialist	FAA	Provide weather briefings to pilots. Assist pilots in reroute around inflight weather hazards.
Aviation Marketing Manager	Kavouras	Provide operationally specific aviation weather forecasts and graphic products for airlines, FSS, and corporate flight departures.
Meteorologist	NWA	Gather, analyze, forecast, and distribute many forms of worldwide weather data.
International Dispatcher	NWA	▪ Authorize, regulate, and monitor flights according to FAA and company regulations. ▪ Compute fuel required for a flight according to the type of aircraft, weather conditions, fuel price differentials, and FARs. ▪ Monitor progress of flights and will delay or recommend cancellation of flight according to conditions. ▪ Adjust flight routings and altitudes to avoid hazardous weather or reduce delays.
Research Applications Engineer	NCAR	Conduct research on improving the ability to detect and predict aviation weather hazards and develop aviation weather products for the aviation industry and airports.

Table 4.1. Observational Fieldtrips

4.2 Information Support Guidelines

A strong cry was heard from dispatchers and pilots alike that simply providing more weather-related information to dispatchers and flight crews would not adequately support effective decision making for routing choices. There is a plethora of weather data available, but what was needed was more context-relevant information to support strategic routing decisions. Based upon interviews, observations, and domain knowledge. a matrix was developed that identifies the weather-related decisions and tasks relevant to strategic routing. In addition to the decisions and tasks, it identifies the constraints or conditions that the decision or task is made under, the current data or sensors that support that decision, and the associated guidelines to support the information needs. The full matrix can be found in Appendix C. Table 4.2 below lists the information-support guidelines that were generated as a result of the analysis of the weather-related tasks and decisions for strategic routing.

Weather Decision/Task	Information Support Guideline
Go/No-Go	▪ Ability to determine minimum weather requirements are met for departure and destination ▪ Ability to determine that crews have enough duty time ▪ Ability to determine aircraft equipped properly to handle this flight in these conditions ▪ Ability to determine my crew is qualified to fly in these conditions
Alternate Requirement	▪ Ability to determine minimum weather requirements are met for alternate
Fuel Requirement	▪ Ability to determine fuel that is required to be carried on this flight
Planned Route and Replanned Route	▪ Ability to plan a path that takes advantage of winds/temperature but avoids potential hazard areas that I want it to avoid (based upon threat level of hazard and may priorities of comfort, time, and efficiency whilst maintaining an acceptable safety level)
Build Situation Awareness	▪ Ability to form big picture of weather (and traffic) hazards that may affect the flight
What if analysis?	▪ Ability to determine consequences to time, fuel, distance, passenger comfort, and safety margins for various routes
Communication	▪ Ability to share information with other interested parties about potential weather hazards and how they may affect routing of flight

Table 4.2. Information Support Guidelines

4.3 Information and Function Requirements

A flight planning task analysis was performed from the viewpoint of dispatcher responsibilities (including weather-related responsibilities in addition to other flight-planning related activities). The tasks required to meet those responsibilities, the system functions required to support those tasks, and the information requirements to support the functions were all identified. The product from this task analysis is a description of the functions that routing tool would have to support along with a listing of the information requirements for a dispatcher routing tool. The task analysis and resultant requirements can be found in Appendix C. Figure 4.2 below shows the overall HCD analysis process. The bolded green arrows depict the main information and function requirements process analysis path taken. A discussion of some of the resultant highlights that may not seem obvious to someone without doing the analysis that our optimizer will attempt to support follows.

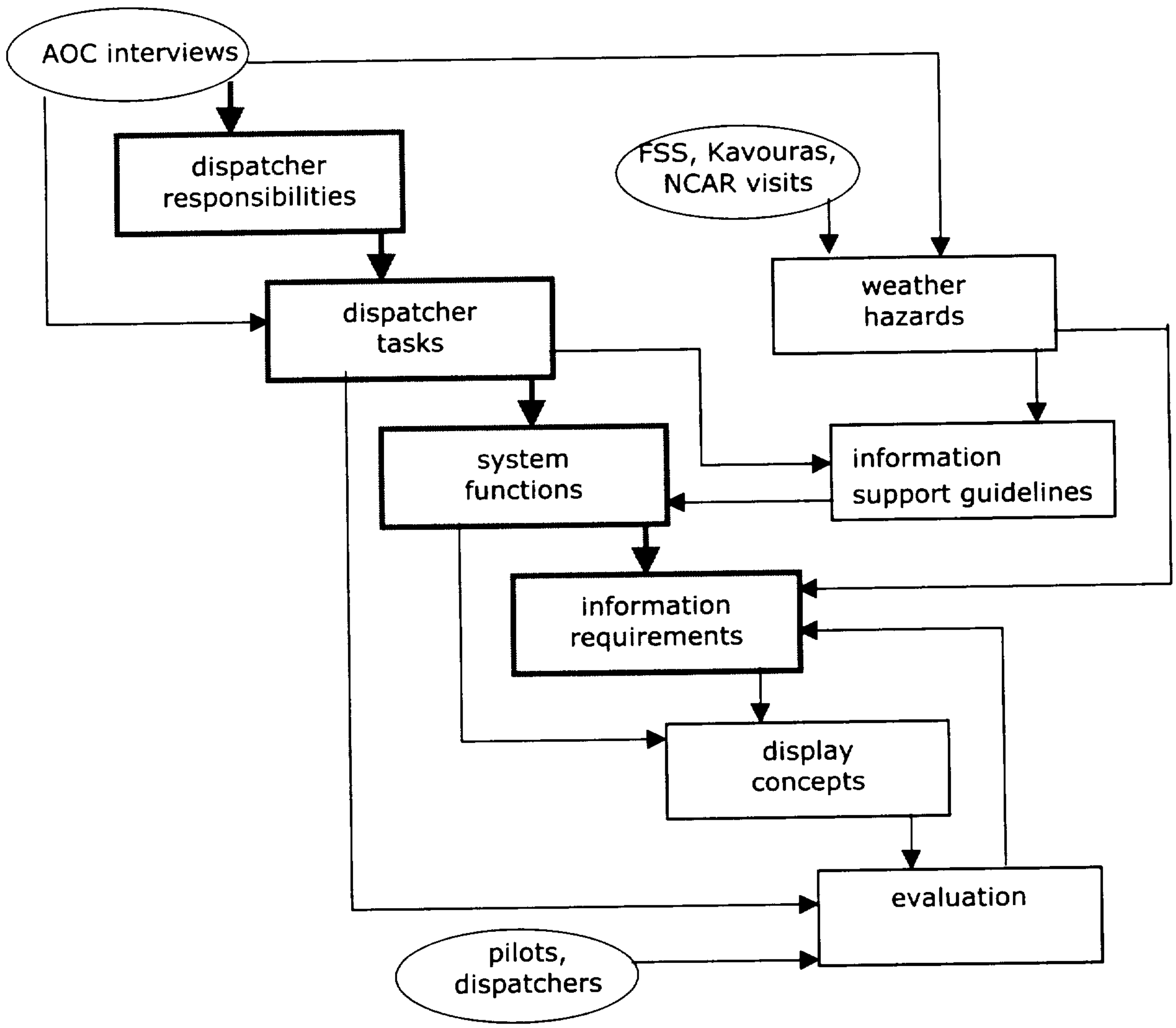


Figure 4.2. Information and Function Requirements Process

Optimization Hierarchy

It was identified that operational tradeoffs were performed by dispatchers (and pilots) to support goal completion. The premise is that, ideally, the goal of flight planning is to generate a route that is safe, is legal, adheres to company policy, is efficient, and is comfortable for passengers and crew. However, during the task of flight planning, inevitably certain desires will be compromised in order to achieve the higher order needs (namely safety and legality). For example, at times, comfort will be sacrificed to gain efficiency (time and fuel), efficiency and comfort will be sacrificed to ensure adherence to company policy of acceptable hazard thresholds (e.g., NWA has very stringent requirements for "acceptable" levels of turbulence that they will plan flights through), and at times company policy, efficiency, and comfort may be sacrificed in order to adhere to legal requirements (e.g., minimum fuel requirements). There may even be a time when a pilot needs to compromise legality, company policy, efficiency, and comfort in order to maintain safety. The identification of these trade-offs imply a functional requirement for the system to allow the user to switch between these operation contexts when flight planning. Figure 4.3 below shows the optimization hierarchy of weather hazard avoidance trade-offs that operators perform to support strategic routing decisions.

Safety
Legality
Company Policy
Efficiency
Comfort

Figure 4.3. Optimization Hierarchy

Flight Plan Decision Making Players

Numerous constraints can affect the routing of a flight, i.e., where you can't go/ where you shouldn't go. Numerous interested parties may want to restrict travel through a particular region. For example, a regulatory agency may prohibit flight over a politically hot region or flight over water because of aircraft type or equipage. An airline policy may restrict flight over a country that may have heavy overflight fees, or may restrict flight through a certain level of predicted turbulence. Although these are not exclusively "weather hazards", they are constraints on the flightplan. Because all of these parties have an interest in the safety of the flight, any one many impose a restriction upon the planned route; hence, they all need the ability to restrict travel or define a no-fly zone. Figure 4.4 below shows the decision making order of constraints upon a flight plan.

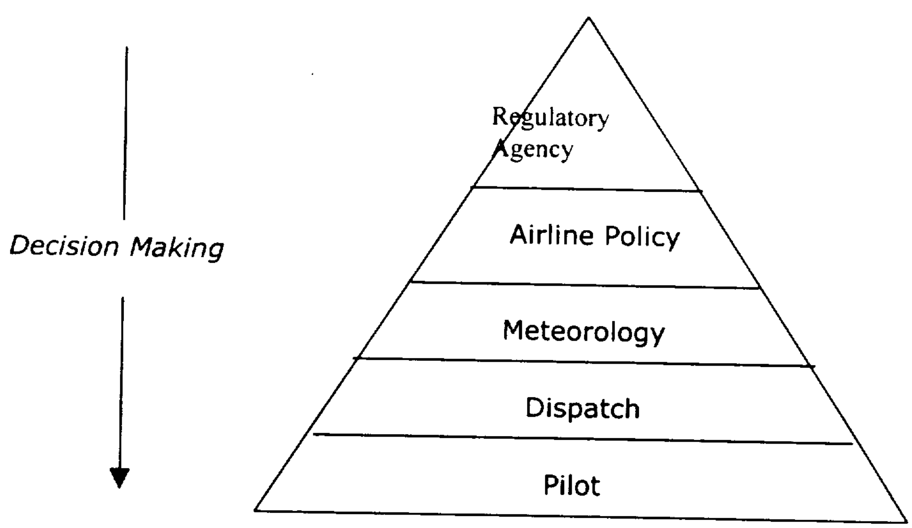


Figure 4.4. Constraints on Flight Path Determination

Hazard Avoidance Maneuvers

As previously mentioned in the report, **Turbulence**, **Icing**, **Volcanic Ash**, **Convective Weather**, and areas of **High Ozone Concentration** were identified as meso-or macro-scale hazards to the aircraft during cruise flight. Note that micro-scale weather phenomena e.g., low-level windshear, wind gusts, etc., were not included because it was felt that these were hazards for tactical avoidance and our concentration is on the strategic avoidance of hazards. The hazards identified all vary in the manner in which they effect the route planning because of their differences the way they effect the aircraft and strategic route planning priorities. The maneuver around a weather hazard will vary depending on the hazard type, intensity, coverage, and location. Some hazards are more often routed around vertically and some horizontally. Table 4.3 below lists hazard type and most commonly associated avoidance maneuver.

Hazard Type	Maneuver
Turbulence	Vertical
Convective	Above or Around
Icing	Vertical
Volcanic Ash	Lateral
Ozone	Below

Table 4.3. Hazard Avoidance Maneuvers

Hazard Levels

Because of the diverse features associated with each weather hazard, some are more easily predicted than others are, and some hazard predictions have higher resolution than others do. By nature, an unstable airmass of convective activity is more difficult to predict; therefore, it is a more subjective forecast. Because of this, one of our recommendations is that the user should be able to delete indicated weather hazards that he or she expects to not affect the flight and insert potential hazards in order to explore contingencies. For example, if the dispatcher anticipates that convective weather may form in two hours ahead of an aircraft, he or she should be able to insert the weather hazard to assess the potential impacts on the flight plan.

As previously mentioned, a hierarchy exists for flightplan optimization. For example, sometimes the operator may be willing to accept a route through occasional turbulence if it results in appreciable fuel and time savings. Sometimes, it may be just as easy to go around an area of known hazard as to go through it because you have time to waste (e.g., you have a required time of arrival to meet). The decision of whether or not to go through a hazard quite often just depends on numerous factors such as time of day, aircraft type, connecting flight requirements, overall schedule delays, conditions at alternates, etc. The ability of trading-off pros (e.g., getting crew and planes to a destination faster) and cons (e.g., bumpier ride) of going through a hazard imply the requirement for multi-level hazard descriptors.

Hazards are amenable to level descriptors by nature of their effect on the operation. As mentioned previously in the report, quite often weather hazards are described with an associated severity index, e.g., severe icing. The question then is how many levels should be used to describe the hazard. Appendix E contains a sampling of some current and experimental weather hazard depictions. Some experimental products contain a scaling of 1-100. Is there any usefulness in knowing that the severity index level is a 67 instead of a 66? Doubtful if (a), the user can not discriminate the risk difference between a 67 and 66; and (b), if the user the user will react the same regardless of whether the severity level is a 67 or 66. The determination of the appropriate number of hazard levels was accomplished by plotting hazard type against reasons why a dispatcher or pilot may want to route around or through a hazard (taken form the optimization hierarchy). Table 4 shows the results.

WX Hazard	Comfort	Efficiency	Company Policy	Legality	Safety	# Levels
Convection		–	–		–	3
Turbulence	–	–	–		–	4
Icing			–	–	–	3
Ash					–	1
High Ozone	–		–		–	3

Table 4.4. Hazard Levels

4.4 Display Concept

This concept represents the integration of human factors and human centered design strategies. All color assignments, along with the proposed display layout and display controls are the result of the integration of human factors guidelines and the preceding analysis of user required functionality. This information is then used to create a conceptual display. The design was continually reevaluated and critiqued - components were altered, removed or added, ideas tried and discarded until a final design is agreed upon. This conceptual display represents the designers best solution to effectively meet required functionality and user needs. It is crucial to note that the optimal solution will be elucidated through an iterative process of evaluation, redesign and re-evaluation by the ultimate end user. It is only through the exercise of this process that omissions, oversights, and mistakes can be identified and corrected. Appendix F contains two static display concepts, one containing "raw data" with overlaid polygons, and the other only showing polygons of hazardous weather areas.

Aviation Conventions

The display design attempted to utilize currently adopted display conventions with the intent of maintaining uniformity where possible, but was not limited to these conventions where they did not serve the identified functionality.

Previous design strategies have employed the notion of the "dark cockpit", advocating subdued colors for normal operations with the aim of reducing eyestrain and increasing readability across environmental conditions. Additionally, the use of black as the background color upon which the display elements are generated is almost universal in current generation aviation displays. Therefore, this same convention was adopted for the AWIN display.

Numerous color and symbology conventions were also adopted for use in the AWIN display and include: magenta colored "active route" elements, magenta colored "sequenced" waypoints, white colored "next" waypoints, airport, navaid, and present position symbology. The placement of the vertical display beneath the lateral display is also a common convention in avionics displays.

The display utilizes a "north up" convention common throughout aviation and existing meteorological displays. In order to accomplish strategic planning activities, the AWIN tool will be required to accommodate the large geographic areas involved in international travel, as well as the large scale of weather phenomena. Several methods of presentation were considered, but a modified conical projection was used.

While this method is not prevalent within the existing avionics display suites, it is not unfamiliar and it is used within meteorological circles. It was felt that any potential difficulties that may arise from the relative newness of the method would be offset by minimization of distortion inherent in the projection of a three dimensional object upon a flat surface. And while not currently used aboard aircraft, pilots are not unfamiliar with this mapping technique. It is used for the depiction of geographic and navigational features in World Aeronautical Charts (WAC) used in flight planning and navigation. These charts are used for strategic planning purposes.

Therefore, is seemed reasonable to conclude that such a method of depiction fits well with the strategic role intended for the AWIN tool. It should be noted that current flightdeck weather displays are designed to support their use in short term, tactical functions. AWIN display design for onboard aircraft use may be different than those used by dispatchers, due to the lack of direct cursor control of display elements, the smaller size and lower resolution available from onboard display hardware, as well as the different task focus.

Meteorological Conventions

No universal convention for the color coding of weather data has emerged, with each data provider using its own color schemes. Therefore, it was determined that a unique color scheme, one that would best support the intended functionality, would be adopted for use in the AWIN display.

Color

The AWIN display was designed for 1024x768 resolution with 8 bit (256) color – a minimum format specification to accommodate the widest range of user equipment. Therefore, the display elements, when used with more capable equipment, should provide even greater levels of distinction between weather phenomena, intensity and coverage.

Each weather hazard is depicted by a single primary color, with intensity of weather coded through gradients of darker (least intense) to lighter (most intense). Since the display was designed with 8-bit color, there were essentially five colors which could be readily differentiated; red, blue, green, yellow, magenta, black, white. Black, magenta and white already assigned as noted. Green was chosen for geographical features and political boundaries due to the high contrast against the black background. Land masses themselves were given a color only slightly lighter than black. The intent was to allow the user to distinguish between landmass, water and political boundary - increasing display readability and situational awareness without distracting from the more important weather information being conveyed. Latitudes and longitudes, along with their respective degree value, were similarly depicted.

Red, with its historical association as a warning, was assigned to the weather phenomenon identified by interview as most important – convective activity. The remaining color assignments were determined in a more arbitrary fashion. Blue – icing; yellow – turbulence; brown – ozone; gray – volcanic ash. Additionally, a distinct "custom" pattern was included to distinguish unique user defined hazard areas, such as active MOAs.

Each hazard color was then assigned a number of color gradients to indicate severity/intensity, with coverage inherent in the graphical display of the phenomenon. For example, convective activity was determined to consist of three distinct levels of intensity while volcanic ash only one. Therefore, three shades of red where used to indicate increasing severity of convective activity. Darkest shades indicate lowest level while lighter shades indicate more severe weather. This convention was dictated by the choice of a dark background environment; lighter shades being most quickly identified. These shades were optimized to provide the maximum differentiation allowed in the 8 bit environment and may not be entirely sufficient.

Since weather phenomena, such as convective activity and turbulence, quite frequently occur in the same vicinity, hazards can cluster on the screen. It was determined that the drawing order of objects should reflect the ranking dispatchers assigned to the different hazards: volcanic activity first, level 3 convection second, followed by level 3 icing, level 4 turbulence and level 2 ozone. While users can filter phenomena to view only those classes of current interest, it was felt that the system should make some provision to present phenomena, where they occur concurrently, in order of importance to the user.

Functionality

Several features of the AWIN tool are envisioned in the display concept. First, using cursor devices, users can create unique hazard area elements in the display and assign various characteristics, such as level of severity. Through manipulation of onscreen elements representing proposed or active routes, the user can initiate and explore various "what if" scenarios to determine the effects of rerouting for weather phenomena. Detailed information regarding specific hazard areas can be obtained by a single "mouse click" on the area of interest and is displayed in the lower right of the display area.

5.0 Use of Weather in Route Optimization

5.1 Goals of Program with Respect to the Route Optimizer

Our objective for phase 1 was to take our existing route optimizer and extend it by adding the capability to consider the presence of weather during the optimization. Some preliminary work had already been done, in the form of demonstrations of the ability of the optimizer to avoid crudely defined 2D static regions. What was missing was the ability to easily define regions that were more representative of actual weather. We also needed to add the capability to display these more general regions in the route optimization display software. Within the optimizer itself, we wanted to explore the ways that the optimization could be influenced by these regions. We had confidence that we could explicitly avoid the regions, but it was less clear how to achieve the more ambiguous goal of discouraging penetration of weather in the context of overall route optimization. Finally, because weather varies over time, we needed to explore characterizations of this movement, and how to incorporate them into our optimization model.

5.2 Goals of Program with Respect to the Route Optimizer

The following is a brief summary of our baseline route optimization framework. More precise technical detail is being prepared in the Honeywell internal document "Route Optimizer", and should be available in early 1999.

The optimization of a route begins with a "cost function" which defines tradeoffs in a formal mathematical manner. The route is said to optimal if it minimizes the integral over the route of this cost for all legal combinations of "state". Using a dynamic program as the solution method, these states are allowed to vary over a quantized grid of values. That grid is searched in a systematic way, proceeding from the origin through all reachable points to the destination. Unfortunately, the number of states for even a point mass aircraft model results in a computationally intractable problem. Fortunately, for longer flights where most of the cost is incurred during the cruise phase of flight, a number of simplifying assumptions can made. Principal among these is that the aircraft can be assumed to be in "quasi-steady" flight, with its altitude, velocity, and flight path angle tuned to balance mechanical and aerodynamic forces with the input thrust level. The lower order dynamic program that results is a search of lateral (2D) space, with an explicit optimization performed in the vertical axis to minimize the "transition cost" between lateral points.

The measure of cost that is typically used for otherwise unconstrained flight is a weighted minimum of fuel consumption and transit time. This results in a transition cost function that looks like:

$$\begin{aligned} \text{cost\_function}(i) &= [FFR(i) + CI] * \text{delta\_t}(i) \\ &= [(FFR(i) + CI] / V(i)] * \text{delta\_s}(i) \end{aligned}$$

where

Waypoint (i) = Current Grid Point
Waypoint (i + 1) = Text Grid Point
FFR (i) = Fuel Flow Rate between Waypoints (pounds fuel/hour)
CI = Cost Index [(non-fuel cost/hour) / (fuel cost/pound)]
V = Velocity between Waypoints (nautical miles/hour)
delta_s (i) = Distance between Waypoints (nautical miles)
delta_t (i) = delta_s (i) / V (i) = Time between Lateral Points (hours)

As described above, this transition cost function is minimized by appropriate choice of FFR (i) and V (i), subject to balance of forces. The transition cost is then added to the accumulated cost at waypoint (i),

accumulated_cost (i + 1) = accumulated_cost (i) + cost_function (i)

to obtain a candidate accumulated cost at waypoint (i + 1). If the grid point corresponding to this waypoint is reached by more than one path, only the lowest accumulated cost (and its associated path) are retained and used as the starting value for the next step.

After all legal waypoint transitions have been traversed, the computation grid contains the information required to reconstruct the optimal path from origin to destination.

5.3 Extension of the Route Optimizer to Include Weather

We will discuss the selection of a prototype model of weather regions that is suitable for use in route optimization and display. Following that will be a discussion of how that model can be used in the route optimizer to define a weather cost component that is minimized in the context of the overall optimization objectives. Finally, we will show extensions to both the prototype weather model and the route optimizer to allow consideration of moving weather.

5.3.1 Prototype Weather Model

Given the limited understanding of weather and available weather products as we started Phase 1, our preliminary weather model was driven by the need to be generally expressive of regions in 2D, while providing a form that would result in a well posed and computationally tractable optimization problem. We also needed a model that could incorporate the notion of movement. Finally, we needed a model that could be extended to 3D during Phase 2 of this program.

Previous route optimizer work with static prohibited regions used a distributed model of the region that corresponded to the search grid used. A cost value would be assigned for every point in the computation grid, with zero used for points outside the region and some non-zero value used for points inside. During the course of optimization, when the algorithm "tried" a particular point, this value would be added to the cost. The advantage of this approach was that it was extremely easy to implement for same rectangular regions of the computation grid.

Disadvantages, however, are numerous:

- For arbitrary regions, the accuracy of the representation is heavily dependent on the choice of grid resolution.
- It doesn't incorporate the property of "in" or "out" of a region, but only a particular set of points. For this reason, it can't be used to evaluate the intersection of a region with a continuous segment of an aircraft trajectory.
- Does not readily accommodate the notion of movement.
- All of the disadvantages listed above become even more problematic if extended to 3D.

Fortunately, other work in a aircraft safety related program and preliminary results from our weather data research led us to a better alternative.

5.3.1.1 Description of Weather Region Boundary as a "Polygon"

Polygons have long been used to approximate arbitrary regions in 2D. Some of the advantages include:

- They have a very compact representation in terms of either vertex points or edge lines.
- They can be easily transformed in order to represent movement.
- Can be easily generalized too 3D polytopes.

Every polygon can be represented as a union of convex polygons (all interior angles < 180 degrees). Using convex polygons, there is a very simple definition of "in" and "out", which leads to a straightforward computation of intersection with line segments. This will be described in more detail below.

For purposes of this study, we have chosen to represent weather polygons by the vertex points, specified as latitude/longitude pairs. The boundary will be defined as a sequence of great circle connections of these vertex points. It should be noted that these regions are not really polygons, because of the curved surfaced of the earth, but that nomenclature already exists in the weather product lexicon, and we will use it.

5.3.1.2 Hazard Characterization

In addition to having a geometric model, each weather region has a hazard characterization that reflects the specific type of weather, together with other factors that would indicate how strongly that particular weather region should be avoided. These factors are still under investigation, and would include, but not be limited to severity, coverage, and probability of forecast accuracy.

5.3.2 Adding Weather to the Route Optimization

Once we have a formal model for the weather, we must consider how that model should be integrated into the existing route optimizer. We will define a weather-cost component of the cost function that builds on the prototype weather model, and discuss how that cost component may be used to influence the optimal route which is produced.

5.3.2.1 Defining a Weather Cost Component for the Cost Function

We can introduce weather into the route optimization by adding a new term to the cost function to represent the "cost" of weather. The magnitude of that term will effect how strongly weather hazards that are encountered will be avoided relative to competing optimization goals.

The general form of a "weather cost" would be:

weather_cost = sum over j of k_weather (j) * weather [j, waypoint (i), waypoint (i + 1)]

where

weather [j, waypoint (i), waypoint (i + 1)] = measure of weather hazard j encounter in the leg connecting waypoint (i) and waypoint (i + 1)

k_weather (j) = weighting placed on the (j)th weather hazard

The definition of "encounter" is somewhat arbitrary, but should be motivated by the safety impact of the particular weather hazard. In an operational system, this definition would be communicated to the optimizer through the aforementioned weather hazard characterization and also by system configuration parameters, which define standards for particular airframes, carriers, operating regions, etc.

Some example quantizations of weather encounter:

1) If a weather hazard should be treated as a prohibited area and, thus, always be avoided,

   Weather = "Large", if the leg from waypoint (i) to waypoint (i + 1) crosses the hazard
   0, otherwise

2) If the safety impact of weather hazard depends on the distance traveled in that hazard, and should be discouraged appropriately,

   Weather = [safety_cost / (nautical mile)] * (fraction of leg in wather hazard) * delta_s (i)

3) If the safety impact of weather hazard depends on the time traveled in that hazard, and should be discouraged appropriately,

   Weather = (safety_cost/hour) * (fraction of leg in weather hazard) * delta_t (i)

It should be noted that both Options 2 and 3 include Option 1 as a special case, for sufficiently large choice of safety_cost. For the demonstration software in Phase 1 of this study, we have chosen to implement Option 2, although we currently believe that most weather decisions will result in the avoid/ignore treatment provided by Option 1.

The value of weighting, k_weather (j), can be used to incorporate operator preference variables to influence the relative cost of particular weather hazards, or hazards of a particular type. It also includes, implicity, scaling to place weather_cost on the appropriate footing relative to fuel, time, and other costs. Further work to define the precise structure of this weighting remains to be done under Phase 2 of this study.

5.3.2.2 Determination that Weather is Encountered

All of the candidate definitions of weather cost above depend on the ability to detect the encounter of a candidate route with a weather hazard. We will discuss the first simple attempt to define this encounter, some of its shortcomings, and a revised solution, which exhibits the required behavior.

The preliminary definition of weather encounter that we adopted was influenced by previous experiments with prohibited areas, as described in the discussion of the weather model. In those experiments, each point in the search grid was assigned a value. If the next waypoint had a non-zero grid value, the leg was considered to be "in" the region, and was penalized some fixed value. If the next waypoint had a zero grid value, the leg was considered to be "out" of the region, and no penalty was incurred.

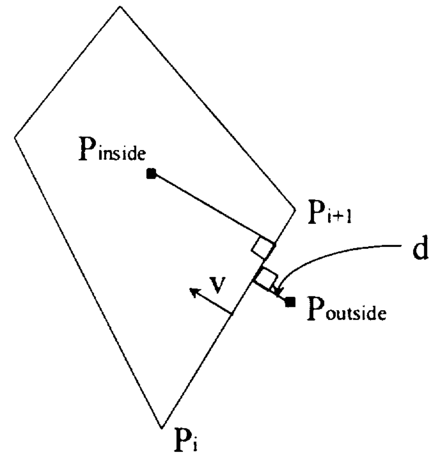
If the weather region is defined not by a grid, but by a polygon, there is an equivalent treatment. We can check to see whether the next waypoint is "in" or "out" of the polygon, and assign the appropriate value. Without loss of generality, we can assume that each polygon is represented as a collection of convex polygons. Each convex polygon can be represented as a set of linear equations representing directed distances of a waypoint from the edges of the polygon.

Assume: convex* polygon
with points specified in
counterclockwise order.

For each polygon segment, define:

$v = P_i \times P_{i+1}$
$d = v \cdot P$
If $d < 0 \Rightarrow P$ outside, quit

If P is not outside of any polygon
segment, it must be inside polygon



* Any polygon can be represented as a union of convex polygons

Figure 5.1. Definition of Weather Encounter Using Next Waypoint

A waypoint is inside the polygon if and only if the directed distance of the waypoint from each of the edges is positive. If the waypoint is inside, the whole leg is considered to be inside.

While this formulation is straightforward, it does have notable problems:

- It does not discriminate between a leg, which is almost entirely outside a weather hazard, and a leg which is almost entirely inside. This is not an issue if it desired to total avoid a hazard, but will yield erroneous results otherwise.

- The reatment of weather is very sensitive to the grid size. If the weather hazard is small enough compared to grid, the dynamic program can, effectively, "hop" right over the hazard.

The later behavior is the most troublesome, and led to a revised solution, which captures the weather hazard encounter in a mush less sensitive manner.

Rather than looking only at the next waypoint of a trial trajectory, we will consider the entire segment from current waypoint to next waypoint, and its intersection with the polygon representing the weather hazard. As it turns out, this problem is identical tot he problem of clipping a line segment against a polygon region for purposes of display in computer graphics, and the same algorithm may be used.

For each polygon segment, define
d_{next}, $d_{current}$ corresponding to P_{next}, $P_{current}$:

If d_{next}, $d_{current} < 0$
=> segment outside, quit

else, if $d_{next} < 0$, $d_{current} > 0$
=> clip P_{next}

else, if $d_{next} > 0$, $d_{current} < 0$
=> clip $P_{current}$

Upon completion, the remaining segment represents the intersection of the polygon and the original route segment

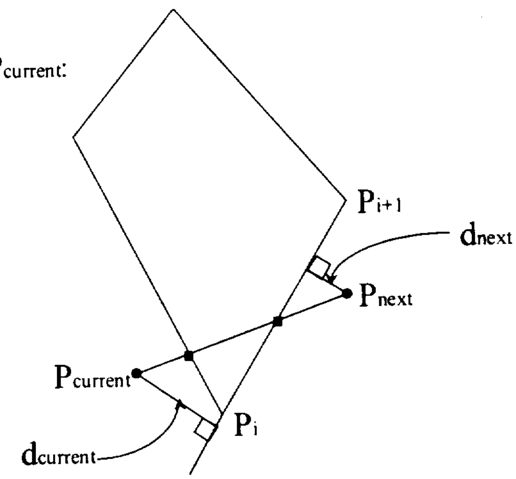


Figure 5.2. Definition of Weather Encounter Using Route Segment

The result of this algorithm will be a line segment which is, in general, only a fraction of the trajectory segment. T he value of the weather encounter will be the fraction of leg distance which is actually spent in the weather hazard which, in the limiting case of no intersection, will be zero. Because the optimization model assumes a constant velocity between waypoints, this fraction will also represent the fraction of time spent in the hazard, should that be of interest.

5.4 Modifications to Account for Moving Weather

The formation described above may be modified to incorporate moving weather. Any continuous change in weather shape and direction can be accommodated, and an optimal lateral route will be produced. For demonstration purposes, we have assumed a common simple representation of moving weather used by both airline dispatch and NCAR, which assumes a fixed shape, but allows movement of the weather centroid along a prescribed direction.

5.4.1 Definition of Additional Region Attributes

In order to extend a static weather polygon to weather which moves along a great circle, the following must be specified:

- <u>Initial Time (Minutes)</u>
  The time at which the given weather hazard will be (or was0 described by indicated vertices. Typically, this value would be some time in the future, and the associated vertex points would incorporate weather model forecast information

- <u>Centered of Motion (Latitude/Longitude Pair)</u>
  The point, which represents the center of motion of the weather hazard.

- <u>Direction (Degrees, Clockwise => North = 0, East = 90)</u>
  The heading of the weather, taken at the center of motion, valid at the initial time. The course of the weather hazard is assumed to lie on the great circle described by this direction.

- Speed (Knots)
  The speed at which the center of motion of the weather hazard moves around the prescribed great circle.

5.4.2 Addition of "Time" State to the Dynamic Program

In order to correctly position the weather hazard in the context of the dynamic program, the value of time must be known relative to some reference such as, the start of the route. Because the dynamic program computes a large number of potential routes simultaneously, it must store the appropriate value of time at every point for all the routes that it is actively considering. When it takes a trial step in a particular direction, the appropriate value of time must made available to weather cost computation function.

5.4.3 Equations of Motion of Moving Weather Polygon

Motion of the weather polygon relative to the fixed earth coordinate system is accomplished by:

1) A coordinate transformation into a reference frame, which is coincides with the prescribed great circle.

2) Rotation of the appropriate angle, which represents the distance traveled in the given time at the prescribed speed.

3) An inverse coordinate transformation back to the original earth fixed coordinate system.

For purposes of the display, the coordinates of the weather polygon vertices are transformed in this manner. For use in the route optimization, where it is desirable to minimize the number of such transformations, an equivalent alternate approach is used. From a weather cost computation standpoint, the only thing that matters is where trial points in the route are relative to the weather. We can use analogous transformations to bring the trial points into the weather center instead of the reverse, thus saving substantial computation for large weather polygons.

5.4.4 Reconciliation of Results with NCAR Sample Data

Using a sample data set from NCAR, we were able to verify the correctness of our implementation of this moving weather model. The NCAR data elements include a set of gridded weather measurements together with a two sets of representative polygons. One of the polygon sets corresponded tot he time that the data was collected, and exactly overlaid with portions of the gridded data. The other set of polygons was forecast one hour into the future, using the same parameterization of movement described above. As a test of our own weather movement software, we transformed the forecast sets back one hour. The result was an exact overlay with the original gridded data and detection polygon sets from NCAR.

5.4.5 Limitations of the Current Approach

- As discussed in the optimizer background, the baseline used for this study assumes an independent vertical axis optimization for altitude and velocity, so velocity is removed as a lateral degree of freedom. Some configurations of moving weather require a change in velocity, "hurrying" in front of weather, or "waiting" for weather to pass in order to achieve the true optimal solution. In these cases, the current prototype will produce a sub-optimal solution.

- Moving weather hazards which cover the destination airport at time of arrival can cause routes which are very sensitive to the choice of weather cost factor and, ultimately, not optimal in any practical sense.

Both of these limitations will be addressed in Phase 2 of the study.

6.0 Plan for 1999 – Phase II

In 1999, from January to September, we will complete Phase II. Our goal for Phase II is to create a prototype decision aid tool and evaluate the tool with dispatchers and pilots. First, we will continue the development of our data set in partnership with the weather industry to include 3-D data. At the same time we will enhance our route optimizer to include vertical routing. We will also code our prototype display based on our conceptual display layouts. After this is completed we will integrate both the route optimizer and the prototype display to create the decision aid tool testbed software. Once we have the decision aid tool, we will bring in dispatchers and pilots to evaluate our concepts using human-in-the-loop simulations. At the completion of Phase II, we will have a prototype decision aid tool that will reside on a PC laptop that can be used to demonstrate concepts to industry. We will also deliver a final report including our findings from out evaluations.

7.0 Appendices

Appendix A. Table of Evaluation of Experimental Weather Products Using Route Optimization Factors

Appendix A. Table of Evaluation of Experimental Weather Products Using Route Optimization Factors

	CDM – CCFP (Collaborative Convective Forecasting Product)	NCAR Convective Detection and Forecast	NCAR Convective Detection and Forecast	NCAR Icing	NCAR Icing	NCAR Turbulence	NCAR Turbulence
Current Status	Experimental 1998	Experimental 1998	Experimental 1999	Experimental 1998	Experimental 1999	Experimental 1999	Experimental 2000
Web site description	http://www.air-transport.org/ops/ccfp/	http://www.rap.ucar.edu/projects/awc/awc.html		http://adds.awc-kc.noaa.gov/		http://adds.awc-kc.noaa.gov/	
Types of Wx	Convective Activity	Convective Activity	Convective Activity	Icing	Icing	Turbulence	Turbulence
Information Source	Collaboration of airline meteorologists	1. Lightening from Global Inc. via Kavouras 2. WSR-88D VIL and tops from National Radar Mosaics by WSI	1. GOES-9 satellite 2. Lightening	1. GOES-8 Satellite 2. Suface Observations 3. RUC model 4. National radar mosaic		1. PIREPS 2. In-situ vertical accelerometer measurements	
International	U.S.	U.S.	Oceanic (Pacific)	U.S.	Oceanic	U.S.	Oceanic
Format	Blobs in bitmap .gif format	Grid with resolution of 5-10 km	*Polygon short term* Future grid of resolution of 5-10 km	Grid with resolution of 20-40 km	Grid with resolution of 20-40 km	Grid with resolution of 20-40 km	Grid with resolution of 20-40 km
Update rate	Twice a day at 1500Z and 1800Z	Every 10 minutes		Every hour		Every hour	
Information contained	Growth indicated by ++, +, NIL, or – Probability of occurrence indicated by high (70-100%), med (40-69%), low (1-39%).	Current storm location (detection) depicted with colors corresponding to VIP levels Cyan polygon and vector indicate location of level 3 storms or greater in one hour	Current storm location (detection) depicted with colors corresponding to VIP levels. Cyan polygon and vector indicate location of level 3 storms or greater in one hour	All icing (or only supercooled droplets) Icing potential from 0-100 indicated in shades of color PIREPs overlaid by letter with size of font indicating severity (large font = mod/sev to sev; medium font = lgt/mod to mo; small font = trc to lgt) C - clear icing X - mixed icing R - rime icing U - unknown icing	All icing (or only supercooled droplets) Icing potential from 0-100 indicated in shades of color PIREPs overlaid by letter with size of font indicating severity (large font = mod/sev to sev; medium font = lgt/mod to mo; small font = trc to lgt) C - clear icing X - mixed icing R - rime icing U - unknown icing		
3D?	Indication of tops (using flight level)	Indication of tops (using flight level)	Indication of tops (using flight level)	Altitudes every 3,000ft up to 25,000ft (composite also available)	Altitudes every 3,000ft up to 25,000ft (composite also available)		
4D?	Vector indicates direction of travel and label number indicates speed of travel (in knots?) Forecasts made at 1500Z and 1800Z for 1800Z, 2000Z,2200Z, and 0000Z.	Cyan polygon indicates the location of level 3 or greater storms in one hour.	Cyan polygon indicates the location of level 3 or greater storms in one hour.			6 hour look ahead	6 hour look ahead
Weighting?	Yellow indicates medium coverage(25-49%), red indicates high coverage (50-100%)	Current storms (detection) use color to indicate 6 levels of storms which correspond to VIP levels green 1-2 yellow 3 orange 4 red 5-6	Current storms (detection) use color to indicate 6 levels of storms which correspond to VIP levels. green 1-2 yellow 3 orange 4 red 5-6	Icing potential from 0-100 indicated in shades of color			

Appendix B. Trip Reports

FSS Visit

An area flight service station (FSS)was visited. The flight service station is a common source of weather information, particularly for general aviation pilots. Pilots will receive an over-the-phone briefing before planning a flight (translate and interpret available National Weather Service (NWS) products describing enroute and destination weather). A standard briefing will include the following items:

- Adverse Conditions that May Affect Route
- VFR Flight Not Recommended (if appropriate)
- Weather Synopsis
- Current Weather
- Forecast Weather (enroute and destination)
- Forecase Winds and Temperatures
- Alternate Routes (if appropriate)
- NOTAMS
- ATC Delays
- PIREPS

In addition to phone services to pilots planning a flight, the FSS will supply weather information to pilots in flight through the enroute flight advisory service (EFAS) aka "Flight Watch". Upon request, the weather dispatcher will provide relevant time-critical enroute assistance if hazardous or unknown weather exists (e.g., locations of thunderstorms and other hazardous weather as reported by pilots or observed on weather radar and satellite) and an alternate or diversionary route is required. Transcribed weather broadcast (TWEB) is also available to pilots enroute and is broadcast continuously over some NDBs and VORs. The data normally includes a synopsis and route forecast on a route-of flight format. All of the information is provided verbally. Some of these services include preflight pilot weather briefings over the phone and enroute flight advisory service (EFAS) or 'flight watch' Weather at all FSS is provided by the NWS via a vendor.

The Princeton Flight Service Station was visited in support of this project. They receive their weather information from WSI who take the NWS products and package them. Currently they have about 150 channels or separate pictures/ charts that they can pull up. They are pulled up by typing a dedicated code (users refer to a cheatsheet). Major aviation weather hazards identified by briefer include thunderstorms, icing, and turbulence. Depending upon type of aircraft and operator, the impact or severity of these hazards on the aircraft varies. Radar is the number one thing they use to give weather reports. Some of the points made about the RADAR display follow.

- The pictures are updated approximately every five minutes.
- Regional and national composites are available.
- WSI and NEXRAD radar pictures are available. There are different color scales between WSI and MEXRAD. NEXRAD goes to purple after red and they are a little different in theyellow/green areas.
- The two modes used include "precip" or "clear". It is important to know which mode you are in because it shifts the scale. One would use "clear" if you want to see where the clouds are.
- On the national composite, you don't know if a station is not reporting. On the regional, you do and this is indicated by a very small magenta square near the station identifier.
- On the national composite, ground clutter is blocked.
- They call the regional radar images "real". Some briefers will use both composite and "real", but some just prefer "real".

- Things to look for in a radar picture:
  - Look at the direction the storm is moving.
  - Look at tops because everyone wants to know how to fly *over* it.
  - Look at history: Is it fast moving, dissipating, intensifying?
  - Microburst is a spat on radar moving in all directions.
  - Different colors mean different things depending on the season, e.g., green in the summer is nothing, but green in the winter is some serious snow with possible icing.
  - Anomalous propagation (AP) – The shape doesn't move at all through a couple updates, corss check references don't match, e.g., surface reports no rain, or you can ask a pilot , e.g., "Hey buddy, our radar reports a big storm off your left wing.... Uh no, it's clear and 65 up here."
  - Rule of thumb is don't fly 20 miles either side of the thunderstorms but of course the pilots push it and do.

Currently, the main reports that weather specialist at the FSS uses in warning pilots of potential turbulence are turbulence:

- Turbulence PIREPs report severe weather it's a c172 or a b747. Same criteria, same reporting but really different interpretation e.g., 50hr private pilot may have a different of interpretation of severe than an NWA captain. NWA I guess can't land in anything categorized as severe so when one NWA reported severe turbulence on landing, FSS issued an uua (urgent PIREP) and so now NWA couldn't land at MSP. NWA called Princeton and said hey, this pilot was overreacting, made a mistake and that is only moderate. Therefore, politics enters the picture and now the report was updated to say moderate to severe turbulence so now NWA can land planes again. There is a clear need for objective measures of turbulence.

SIG WX Chart

Every maker has its own coding, but for theirs:

Red – Ifr
Yellow – Low-level Turbulence
Green – Upper-level Turbulence
Black – Mountain Obscuration
White - Icing

SA Reports

- Surface analysis issued min. hourly at :55 - :00. International METAR format includes time issued, temperature, dewpoint, wind, visibility precip, notams, etc. (I have format at my office) and if it is AWOS station.
- Any major change in WX and they issue "special" updates and also some give reports 3x/hr.
- Most are automated AWOS reports.

How do you know if there is a problem in automated reporting and report isn't to be believed?

- Need to crosscheck with other stations nearby.
- Items are missing, e.g., temperature.
- Values are outside acceptable parameters, e.g., dewpoint reported higher than a temperature, last wind reported was 3605 and now wind is 2445 and there is a high pressure system over area ..... Just doesn't make sense.
- PIREP conflicts, e.g., may not be cloudy but instead a bug has crawled across the mirror or frost has built up.
- Temperature and dewpoint are the easiest sanity checks.

Northwest Visit

We met with the Chief Flight Dispatcher, International, observed a surface meteorologist working on identifying, a senior meteorologist participating in the collaborative convective plot, and observed an international dispatcher on the job. The goal of the AOC is to route around weather strategically; that is, route around weather at a systems level on the ground. Tactically rerouting costs $100 million annually. The problem with flightplanning is that you are trying to mesh two areas of uncertainty: weather and traffic prediction. Because the TMU is undefined – you don't really know where the hold-ups in the system are going to be, and you don't really know where the bad weather is going to be, it difficult to attain resolution. They identified the top aviation weather hazards that they route around include turbulence, thunderstorms, icing, volcanic ash, and high concentrations of ozone. Because of their hubs in Minneapolis and Detroit, they have particular interest in winter-related hazards where other airlines may not.

There are numerous sources of weather information; there are thousands of different charts that they have access to whether they come from their weather provider, NWS, or the internet. "We don't want more information, we want more relevant information". -- more relevant to flight planning -- He said that it is better to just give me a space where you know it (weather, traffic) won't be instead of where it will be.

In house, they draw up "TPs" or turbulence plots, though they are not limited to only turbulence, they are polygons that are hand drawn to depict aviation weather hazards. These hazards then have annotations associated that provided relevant information e.g., altitudes affected, percent of coverage, severity, etc. Northwest does an excellent job of predicting turbulence and they sell a turbulence prediction product to other airlines. They say that turbulence avoidance is not reactive, but something you plan for on the ground. They work very hard at monitoring the atmospheric conditions regularly and it is this frequency of attention to the hazard that make them good at avoiding it.

Currently, Northwest uses a flight planning system was bought from United in 1988. The system is mainframe based, written in FORTRAN, and uses fixed routes in its optimization routines. They will be acquiring a new flight planning system from Jeppesen (Southwest currently uses) which will be able to calculate a 4D trajectory with a cost index, which can be chosen for each flight. The system will calculate the optimal route using straight lines (not curves). The dispatchers and pilots are trained more on weather than pilots.

Interview Notes: Information bombardment. Jeppesen Weather produces over 1200 maps daily, from worldwide Significant Weather maps, which include Turbulence, Icing, Convective Areas, Volcanic Ash Plumes.

Kavouras

Company located in Burnsville, Minnesota, provides many FSS (The FSS we visited received weather graphics from the vendor WSI) as well as AOCs with weather graphics. Kavouras will customize International briefing service is used by some airlines and is given verbally from a weather specialist over the telephone to the pilot/dispatcher. A typical set-up includes a workstation with four graphics menus: current, forecast, satellite, and radar, although customizable features are available (for an additional price!).

Current Charts

Weather Depiction – Contoured and shaded depictions of MVFR and IFR. This chart provides the user a general overview of the country in terms of ceiling and visibility. Additional synoptic features include highs, lows, and fronts. It is useful in building a macro-scale picture.

North American Surface – Isobars, highs and lows, and fronts.

National Radar Summary – Composite of the 211 NWS, military, and ARTCC radars depicting precipitation areas using the standard VIP scale of six intensity levels.

VIP Level	Contour Color	Intensity Level
1	Light Green	Light
2	Dark Green	Moderate
3	Light Yellow	Heavy
4	Dark Yellow	Very Heavy
5	Light Red	Intense
6	Dark Red	Extreme

Upper Air – At 850, 700, 500, 300, and 200 mb, display height contours in decameters, temperature C°, relative moisture, and wind kts. The following table provides an approximate relationship between millibar level and altitude (the actual altitude of these levels varies significantly with season and latitude).

MB	Altitude (ft)
850	5,000
700	10,000
500	18,000
300	30,000
200	39,000

Freezing Level – Displays the height in intervals of 4,000' of the lowest freezing level in thousands of feet above the surface taken from NWS balloon soundings taken twice daily at 0000Z and 1200Z.

Lifted Index/K Index – two values for atmospheric stability displayed from 0000Z and 1200Z radiosondes. The Lifted Index top value if negative indicates an unstable atmosphere and positive indicates stable atmosphere. and the K Index bottom value if larger indicates the greater the likelihood of precipitation.

Perceptible Water – displays a contoured analysis of the liquid water in a vertical column of air, which can be equated to precipitation total. The greater the number, the greater amount of moisture that the atmosphere is holding and would be possible from an air mass given the appropriate conditions.

Average Relative Humidity – Gives the average humidity from the surface to 500mb. Humidity values are contoured every 10% in red.

Winds Aloft – Displays wind barb data for 4000', 14,000', 24,000', and 34,000'msl.

Forecast Charts

North American Surface – Depicts highs and lows, fronts and precipitation. Available for 6-, 12-, 24-, 26-, and 48- hr time periods?

Low-level Significant Weather – Depicts freezing levels, mvfr and ifr, and turbulence areas from the surface to 24,000' available for 6-hr time period.

Winds/Temperatures Aloft – Depicts NWS forecasts which are issued twice daily for 6-, 12-, 24-, 26-, and 48- hr time periods?? Windbarbs and C° are displayed for 800, 700, 650, 500, 400, 300, 250, and 200mb.

U.S. High-level Significant Weather – Displays jet stream axes with altitude and wind maximums, tropopause heights, areas of broken thunderstorm coverage, areas of moderate or greater turbulence, and surface fronts.

36-Hr Thickness/Sea Level Pressure – Depicts sea level pressure, frontal features, and thickness of atmosphere 36-hr in the future

Geostationary Operational Environmental Satellite (GOES) – GOES imagery (infrared and visible) available every half hour (animated historic perspective)

Radar Chart

- National Radar Composite – NWS is available at 5-min intervals with animation.
- Regional Radar Composite – 20 regional radar composites available every 5 min. Shows high-resolution radar data along with stations not reporting.
- Single Radar Imagery – Animation available. Ground clutter can be filtered.

Interviewer Notes: Wow, like the FSS visit, it is obvious that many different products are available and distributed. However, clumsiness of going between all the different products is apparent. Example., some altitudes are msl, some are agl, and yet some don't even provide altitudes, but rather millibar levels. Greater resolution is required, e.g., 4000' intervals for icing report, more consistency in units applicable to flight planning (flight levels), and obviously more integrations. It's not that these reports shouldn't be available to the dispatcher (or pilot for that matter), it's that products need to be made available (developed in conjunction with NCAR?) that are more applicable to flight planning.

NCAR Visit

Automated products that integrate diverse sensors and algorithms for pilots, ATC, and AOC.

3 WX Hazard Nowcast Products

- Convective
- Icing
- Turbulence

Oceanic Convective Products

- 1 hr. look ahead every 10 minutes
- 4-5 km spaced datapoints
- 2D, tops, intensity, plus time
- Look at satellite, optical flash rates, VLF lightning data, radar (not available internationally), soundings (not available internationally), Mesonet (not available internationally), etc., and use quality control and detection algorithms.

Icing and Turbulence Products

- Better than humans on icing, almost better than humans on turbulence
- 6 hr. look ahead every hour
- 20-40 km x 1000'-2000' for datapoints
- Look at AutoPIREPS, PIREPs, Satellite, Sounding (not available internationally), Anemometer (not available internationally), Lida (not available internationally) r, Profile (not available

internationally), Radar (not available internationally), surface ob (not available internationally) s, etc., and use quality control and detection algorithms.

Pilot Interview

- Currently, use WSI for wx on ground and in air. The only graphical product they receive is of radar, and satellite, everything else is textual including FTs of departure and destination, METARs of departure, destination, and stations along route, Sigmets, Airmets, Convective Sigmets, and FDs.
- Pilot initiated air display (AirShow) of text information, radar, and satellite. This is done over the telephone and can take 5 minutes to receive back the information. They have an extra screen on the overhead panel where it is displayed.
- If there is bad weather, then they will use the AirShow, otherwise they wont.
- Customization desirable e.g., wx mins, how often to change alt.
- Guidelines: lateral 15min, vertical hourly
- Would check to modify flt plan hourly
- Current weather related decisions that they make in flight planning include determining weather or not an alternate is required and how are the winds going to affect my fuel consumption. They strictly adhere to the FARs regarding weather requirements with the exception of takeoff. They require 600 RVR or lowest published on charts, whichever is greater, they wont shoot a circling approach unless they are forecast or have a 1000' ceiling and 3 miles visibility, and no circling at night. They won' fly without the weather radar onboard the aircraft working unless they are VMC in the day or night with assurance of no convective activity. They won' fly closer than 20 miles from red on the weather radar when they are at altitude.

Interviewer Notes: clear need for "acceptable" weather hazards customization. There are different levels of hazards, what is safe, what is regulatory, what is company policy, what is comfortable, etc.

Appendix C. Information Support Guidelines

Tasks and Decisions	Who	Conditions/Constraints	Current Support Data/Sensors	Info-Support Guideline
Go/ No-Go	Dispatch Pilot-in-Command (PIC) has final authority	Federal aviation regulations (fars), company policy, or aircraft type have minimum acceptable values for the following weather variables at *departure*, *destination*, and *alternate*(s) airport including: Visibility i.e., prevailing, runway visibility value (rvv), runway visual range (rvr), or vertical visibility Ceilings Wind Thunderstorms Runway Surface Conditions Density Altitude rwy Length Required Turbulence – Microburst, Windshear, Gust Fronts Icing Heavy/Freezing Precip Temperature/Dew-point Aircraft Readiness including: Minimum Equipment List (mel) Configuration Deviation List (cdl) Crew Duty Time Crew Currency Qualifications (e.g., cat ii, cat iii landings)	Surface Observations Previous Flights radar Radat Soundings Mesonet Satellite Infrared, Visible PIREPs Autopireps Anemometer Lidar Profiler llwas	▪ Ability to determine minimum weather requirements are met for departure, destination, and alternate. ▪ Ability to determine that crews have enough duty time ▪ Ability to determine aircraft equipped properly to handle this flight in these conditions ▪ Ability to determine my crew is qualified to fly in these conditions
Alternate Require-ment	Dispatch	WX at alternate must meet the requirements of fars and/or operator's operations specifications for	surface observations previous flts radar	▪ Ability to determine minimum weather requirements is met for departure, destination, and

		Visibility, i.e., prevailing, runway visibility value (rvv), runway visual range (rvr), or vertical visibility Ceilings Wind Thunderstorms Runway Surface Conditions Density Altitude rwy Length Required Turbulence – Microburst, Windshear, Gust Fronts Icing Heavy/Freezing Precip Temperature/Dewpoint	radat soundings mesonet satellite infrared, visible PIREPs Autopireps anemometer lidar profiler llwas	alternate.
Fuel Require-ment	Dispatch PIC has final authority	Winds Aloft Possible Diversions Alternates Required Enough fuel to fly to and land at release airport and to fly and land at most distant airport and fly for an additional 45 min.	Winds Aloft Forecast (fd)	▪ Ability to determine fuel that is required to be carried on this flight
Planned Route and Replanned Route		**Fuel/Time Efficiency Desired (priorities)** **Potential Weather Hazards** Fronts (type & intensity – availability of moisture, stability of air being lifted, speed of frontal mvmt, slope of the front, and the moisture and temp between fonts) *Fast Moving Cold Front* (turb, precip, strong gusty winds, squall line 50-200 mi ahead) *Occlusion* (wx conditions change rapidly, more sever begin, precip. low vis, strong winds around	Cost Index PIREP Winds Radar Satellite SIGMET, convective SIGMET	▪ Ability to plan a path that takes advantage of winds/ temp but avoids potential hazard areas that I want it to avoid (based upon threat level of hazard and my priorities of comfort, time, and efficiency whilst maintaining an acceptable safety level)

		intense low at the north end) *Showery Precip near Warm Front* (thunderstorms) Windshear (assoc w/ temp inversion, jet stream, thunderstorms, and frontal inversions – cold after, warm before) Turbulence (type & intensity) *Mechanical* – strong winds flowing perpendicular to mountain ridges and unstable airmass = leeward side downdrafts, stable airmass = mountain waves which may extend 100 nm downwind *Cat* – often develops in or near jet stream (narrow band of high altitude winds near tropopause) when it interacts with a large mountain range or deep low press system. cat can be expected when curving jet strm on polarside of a deep low-pressure system and can be violent on low press side of jet strm. Frequent in an upper trough on the cold (polar) side of the jet strm. in absence of jet strm, cat can occur with sharply curved contours of strong lows, troughs, and ridges aloft and in areas of strong, cold or warm air advection. mtn waves can cause cat. *Thunderstorms* – tornadoes, squall lines, turbulence, hail, icing, electricity (lightning, precipitation static) lightning Icing - clouds at or near subfreezing temperatures have potential. heaviest	**PIREPs, Autopireps, Soundings, Anemometer, Radar, Profiler, Lidar, Satellite** Cirrus Clouds = Turb, Canopy Static (particles brushing against plastic a/c sfc interfere with radio recep) Observed Wind and Temperature Aloft Chart (2x/day) for fl240, fl300, fl340, fl390 Tropopause Data Chart: Observed Data Panel (missing data usually indicates strongest wind!); Tropopause hgt/Vertical Wind Shear Prog (expect mod turb when vert wnd shr > 6kts) High-level Sig WX Prog (embedded cb; squall line; sandstorm or duststorm; jet stream; front sfc position, speed, direction; tx, cyclone, satellite, radar, mesonet, soundings, PIREPs, Autopireps ir satellite and visible) Forecasts	

		icing found at or slightly above the freezing lvl. Convective activity (probability and intensity) Volcanic ash Ozone concentration ATC, overflight fees, prohibited areas		
"Situation Awareness"		Macroscale weather pattern synopsis included frontal and pressure systems during the forecast valid period and flight hazards associated with those weather systems. Weather advisories for severe thunderstorms (surface winds > 50kt, hail > 3/4", and/or tornadoes), or other convective activity, forecast sky cover, cloud tops, visibility (including vertical visibility), stability and moisture of air, freezing levels; weather and obstructions to vision (e.g., smoke from forest fires) for a corridor along route	Convective SIGMET (wst) SIGMET (ws) AIRMET (wa) Convective Outlook (ac) Severe Weather Watch Bulletin (ww) Surface Analysis Chart Weather Depiction Chart Radar Summary Chart Low-level Significant Weather Prog High-level Significant Weather Prog (int'l) Composite Moisture Stability Chart	▪ Ability to forma big picture of weather (and traffic) hazards that may affect the flight
What if Analysis?	Dispatch and Pilot	Possible hazard locations, overflight fees, fuel prices, traffic flow	Weather Forecasts	▪ Ability to determine consequences to time, fuel, distance, passenger comfort, and safety margins for various routes
Communi-cation	aoc, pilots, atc	Display Clutter Trying to share spatial information either verbally or textually		▪ Ability to share information with other interested paries about potential weather hazards and how they may affect routing of flight.

Appendix D. Dispatcher Task Analysis

		Functions		
Responsibilities	Tasks	Input	Output	Information Requirements
Maintain Flight Safety	Plan Weight and Balance	Aircraft Type	Fuel Use	Required Fuel
		Company Route		
		City Pairs		
		Payload		
		Winds		
		Temperatures		
		Departure/Arrival		
	Plan Fuel Requirements		Fuel Amount	Required Fuel
	-Burn			Expected Burn
	-Reserve			Expected Reserves
	Avoid Adverse Weather Impacts	Weather Type	Weather Conditions	Weather Type, Conditions, Lateral Position, Vertical Position, Severity
		Location	-Current	Weather Severity, Movement History, Coverage, Probability
		Forecast Time	-Projected	Weather Predicted Movement, Growth or Dissipation
			Constraint Level	Hazard Level, Constraint Level
			-No Fly	
			-Optional	
		Define No Fly Zone	New Route, Time, Fuel	No Fly Zone, New Route, Times, Fuel
		Delete No Fly Zone	New Route, Time, Fuel	No Fly Zone, New Route, Times, Fuel
		Force Route	New Route	New Route, Times, Fuel
	Avoid Obstructions		Obstructions, NOTAMS	Obstructions
	Plan Landing Weight		Projected Landing Weight	Projected Landing Weight
	Plan Contingencies	Define No Fly Zone	New Route, Time, Fuel	No Fly Zone, New Route, Times, Fuel,

		Functions		
				Costs
		Define No Fly Zone	New Route, Time, Fuel	No Fly Zone, New Route, Times, Fuel, Costs
	-Destination Down	New Destination	New Route, Time, Fuel	New Route, Time, Fuel
	-Alternates Down	New Alternates	New Route, Time, Fuel	New Route, Time, Fuel
	-Weather Delays	Define Holding	New Times and Fuel	New Times and Fuel
		-Place		
		-Time		
		Define No Fly Zone	New Route, Time, Fuel	No Fly Zone, New Route, Times, Fuel
		Delete No Fly Zone	New Route, Time, Fuel	No Fly Zone, New Route, Times, Fuel
		Force Route	New Route, Time, Fuel	New Route, Times, Fuel
	-Traffic Delays	Define Holding	New Times and Fuel	New Times and Fuel
		-Place		
		-Time		
	Decide Go/No-Go	New Fuel, MEL/CDL, No Fly Zones	No Feasible Route	Message, Constraining Factors
Maintain Legality				
	Assess MEL/CDL Impacts on Route Availability	No Fly Zones	New Route, Times, Fuel	
	Assess Flight Qualifications for Route			MEL/CDL, Aircraft Qualifications, Crew Qualifications
	Assess Route Conditions for Aircraft and Crew			
	-RVR	New Destination	New Route, Times, Fuel	RVR, Aircraft and Crew Qualifications, New Route, Times, Fuel
	-Drift Down	Define No Fly Zone	New Route, Times, Fuel	MEL/CDL, Aircraft Qualifications, New Route, Times, Fuel
	-Over Water	Define No Fly Zone	New Route, Times, Fuel	MEL/CDL, Aircraft Qualifications, New Route, Times, Fuel
	-ETOPS	Define No Fly Zone	New Route, Times, Fuel	MEL/CDL, Aircraft Qualifications, New Route, Times, Fuel
	-Outside CONUS	Define No Fly Zone	New Route, Times, Fuel	Aircraft, Crew Qualifications, New

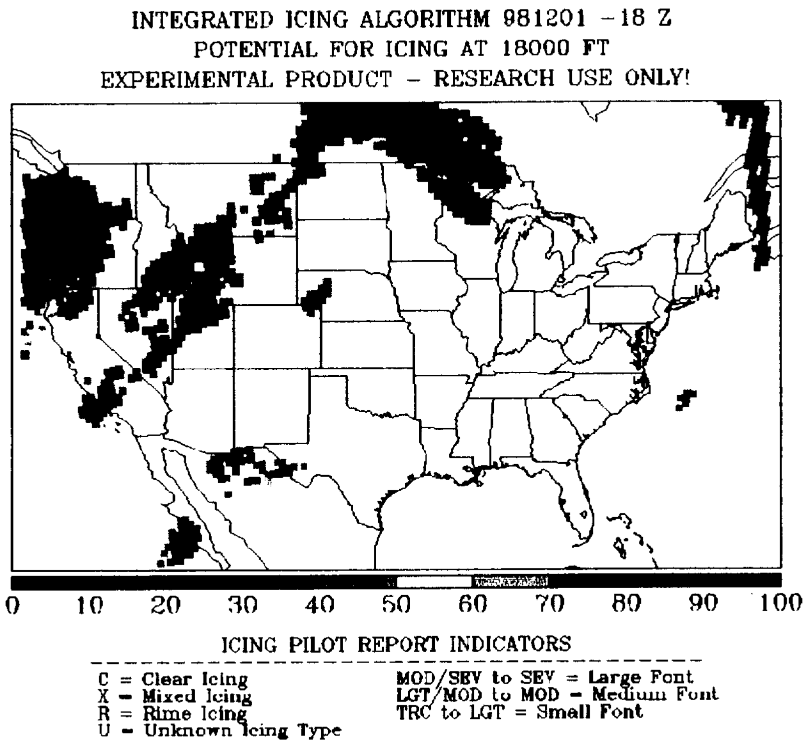
		Functions		
				Route, Times, Fuel
	-Runway Contamination	New Destination	New Route, Times, Fuel	MEL/CDL, Aircraft Qualifications, New Route, Times, Fuel
	-Noise	New Departure/Arrival, Route	New Route, Times, Fuel	Noise Sensitive Areas, New Route, Times, Fuel
	Assess Alternates			
	-RVR	New Alternate	New Route, Times, Fuel	RVR, aircraft and crew qualifications, new route, times, fuel
	-Drift Down	Define No Fly Zone	New Route, Times, Fuel	MEL/CDL, Aircraft Qualifications, New Route, Times, Fuel
	-Over Water	Define No Fly Zone	New Route, Times, Fuel	MEL/CDL, Aircraft Qualifications, New Route, Times, Fuel
	-ETOPS	Define No Fly Zone	New Route, Times, Fuel	MEL/CDL, Aircraft Qualifications, New Route, Times, Fuel
	-Outside CONUS	Define No Fly Zone	New Route, Times, Fuel	aircraft, crew qualifications, new route, times, fuel
	-Runway Contamination	New Alternate	New Route, Times, Fuel	MEL/CDL, Aircraft Qualifications, New Route, Times, Fuel
	-Noise	New Departure/Arrival, Route	New Route, Times, Fuel	Noise Sensitive Areas, New Route, Times, Fuel
	Avoid Restricted Areas	No Fly Zones	New Route, Times, Fuel	restricted areas, new route, times, fuel
Maintain Company Policy				
	Overflight Fees	Force Route (ignore fee)	New Route, Times, Fuel, Costs	New Route, Times, Fuel, Costs
	Political Restrictions	No Fly Zones		New Route, Times, Fuel, Costs
	Turbulence Penetration	No Fly Turbulence Levels	New Route, Times, Fuel	New Route, Times, Fuel
	Facilities and Equipment at Alternates			Alternate Equipage
Maintain Flight Efficiency				
	Plan Time	Route	Times	
	Determine Fuel/Time Cost Tradeoff	Fuel/Time Balance		
	Determine Comfort/Efficiency	Turbulence Levels to	Route Alternates	Route Alternates,

		Functions		
	Tradeoff	Penetrate		Times. Fuel. Costs
	Determine Climb and Descent Profiles			
	Determine Cruise Altitude	Winds. Turbulence. Icing. Ash		Safe Altitudes
	Determine Speeds			
	Compare Alternatives	Save Conditions. Results	Alternatives. Times. Costs	Alternatives. Times. Costs (numbers. graphic)
Maintain Passenger Comfort				
	Assess Turbulence	Turbulence Positions. Levels	Turbulence Positions. Levels	
	Determine Comfort/Efficiency Tradeoff	Turbulence Levels to Penetrate		
Balance Safety. Legality. Policy. Efficiency. Comfort		Level of Comfort. Efficiency to Be Sacrificed	Route of Comfort around Level 1,2,3,4 Hazards	
			Route of Efficiency around Level 2. 3. 4 Hazards	
			Route of Company Standards around Level 3. 4 Hazards	
			Route of Safety/Legality around Level 4 Hazards	
		Custom Parameters (ignore specific weather type or level. no fly zone. fee zone)	Route of Custom around Acceptable Hazard Levels by Hazard Type	
Maintain Fleet Efficiency				
	Manage Resource Connections			
	-Crew			Connecting Flights for Crew
	-Equipment			Connecting Flights for Equipment
	-Passengers			Connecting Flights for Passengers
	Manage Schedule			
	-Cancel Flights			
	-Change Connections			
	-Originate Ferry Flights			
	-Assess Time of Day Requirements		Time of Day	Projected Schedule Impacts
Coordinate with ATC				
	File Flight Plans	Flight Plan	Accepted. Rejected. Changed	New Route. Times. Fuel. Costs

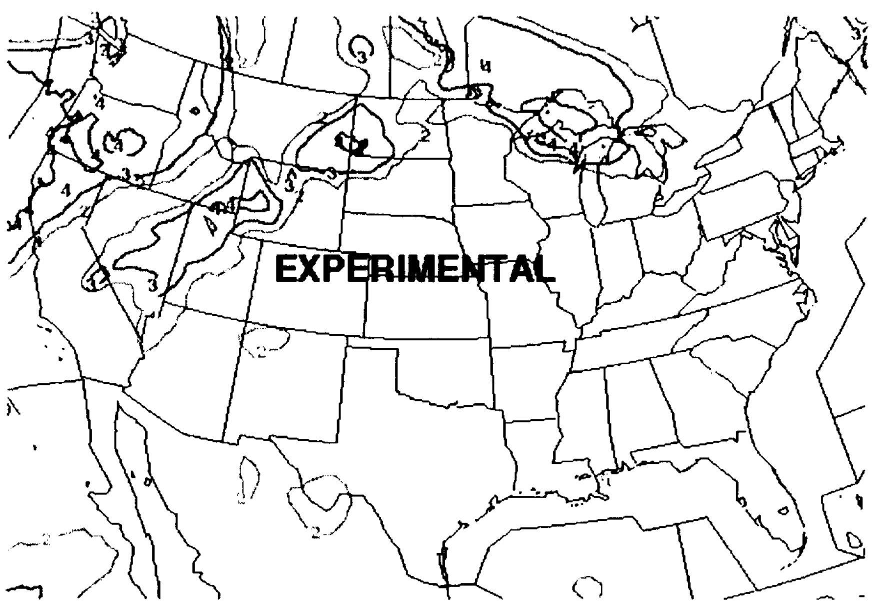
		Functions		
	Negotiate Routes	Proposed Routes		Route
	Explain Route Selection Rationale	Explanatory Notes	Explanatory Notes	Explanations
Coordinate with Pilot				
	Send Flight Plans	Flight Plan		Flight Plan
	Evaluate Proposed Route Changes		Times, Fuel, Costs	Times, Fuel, Costs
	Negotiate Route Changes	Proposed Routes		Routes
	Explain Route Selection Rationale	Explanatory Notes	Explanatory Notes	Explanations
Coordinate with other AOC Functions				
	Crew Scheduling			Crew Time Limits
	Maintenance			Aircraft Time and Location Limits
	Contingency			
	ATC Coordinator			Routes, Explanatory Notes
	Meteorology			Weather Descriptions
	Aircraft Routing			Aircraft Limits
Monitor Flight Progress				Aircraft Location, Altitude, Speed, Plan, Time to Hazard
	Fuel Burn			Fuel Burn
	Destination Status			Destination Status (runways, RVR, limits)
	Alternates Status			Alternates Status (runways, RVR, limits)
	Weather			Weather Conditions
	Equipment Status			Equipment Availability

Appendix E. Example Weather Formats

Appendix E. Example Weather Formats



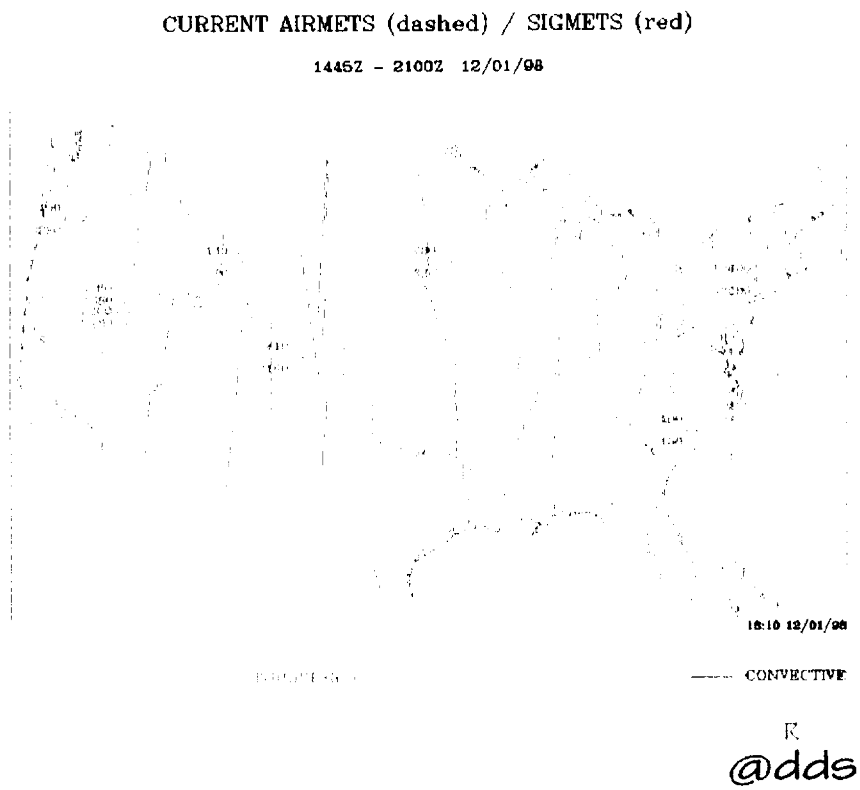
http://adds.awc-kc.noaa.gov/
This is one of the experimental products we saw on our NCAR visit.



981202/0000V003 FL140-FL300 COMPOSITE RUC2 NEURAL NETWORK ICING

http://www.awckc.noaa.gov/awc/nnice_15.html
This is an experimental product from The Experimental Forecast Facility at the Aviation Weather Center. The maps of icing intensity available above are composites of the output of two neural networks taught to

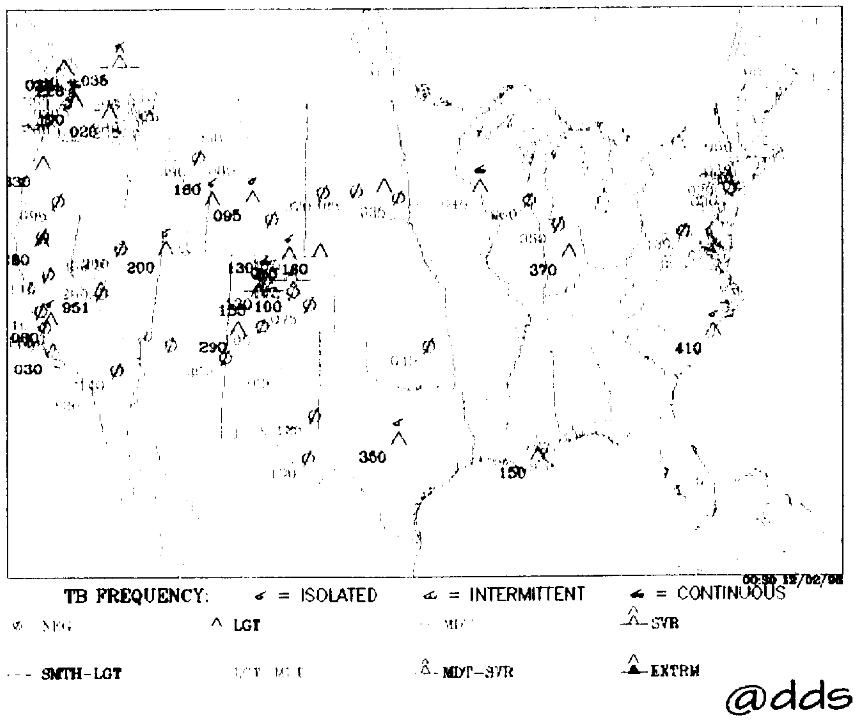
predict icing intensity from input data of temperature, relative humidity, and convective potential from the Rapid Update Cycle model. Actual output to the Aviation Weather Center forecasters is in layers approximately 1000 ft thick. The output values range from zero to six with zero representing no icing and six severe icing. A two is light icing and a four is moderate icing. The contours begin at the two levels. While fours are very common, a five (moderate to severe icing) is rare. Because of the contouring routine, you will never see a six.



http://adds.awc-kc.noaa.gov/
This is graphical representation of airmets/sigmets.

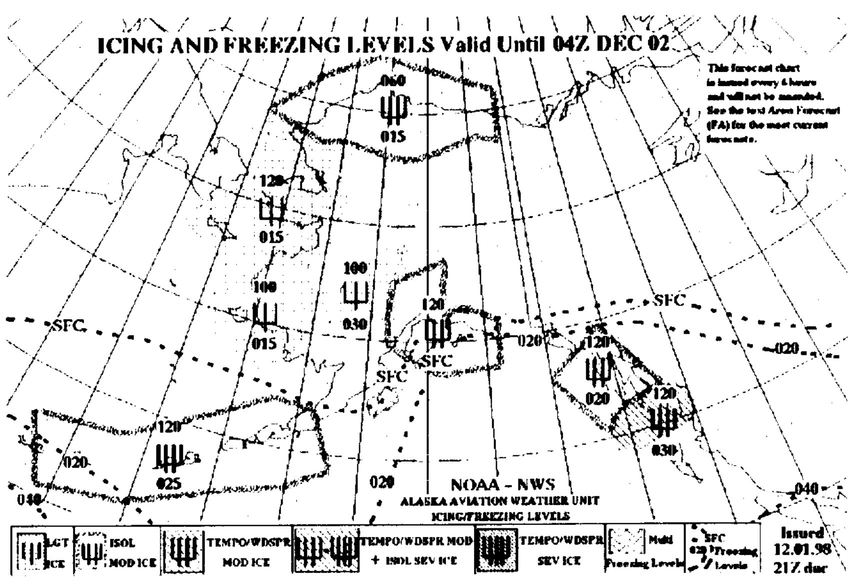
Pilot Reports (PIREPs) of Turbulence

2223z 12/01/98 - 0016z 12/02/98



http://adds.awc-kc.noaa.gov/

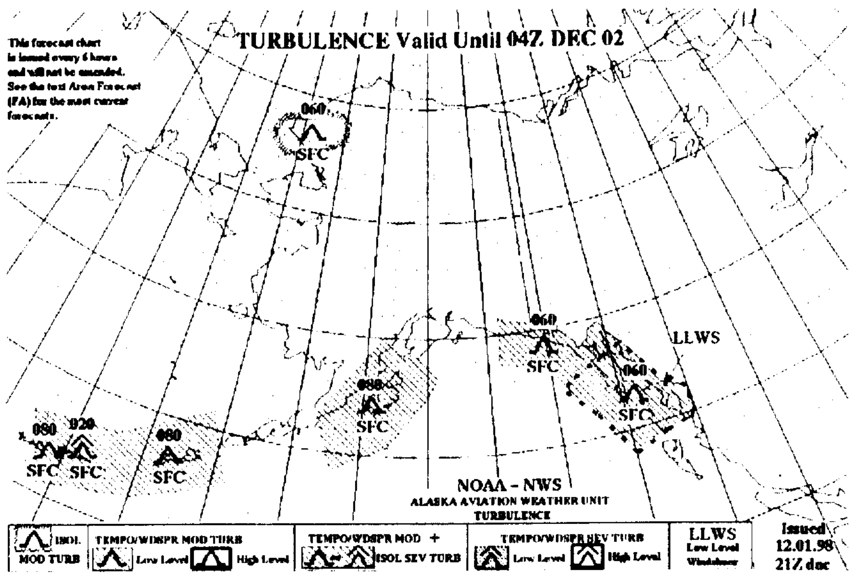
This is a graphical representation of PIREPs. Imagine what an autopirep one wouuld look like in this format!!



http://www.alaska.net/~nwsar/html/aawu/icg.html

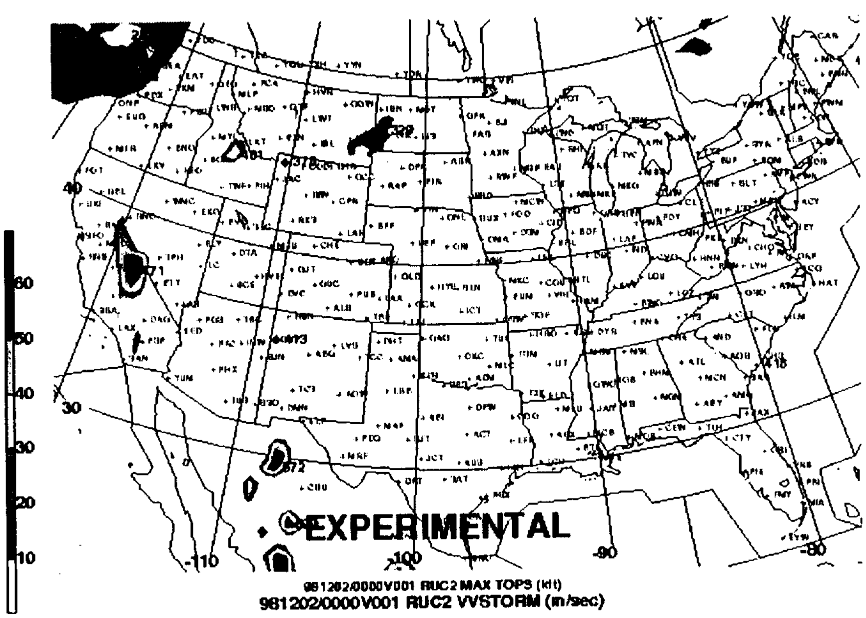
This is from the Alaska Aviation Weather images, created by forecasters at the National Weather Service Forecast Office in Anchorage. These images are based on current satellite images, model data: observations, and forecaster knowledge of the local area.

Note that in addition to severity, coverage level is represented i.e., widespread, or isolated.



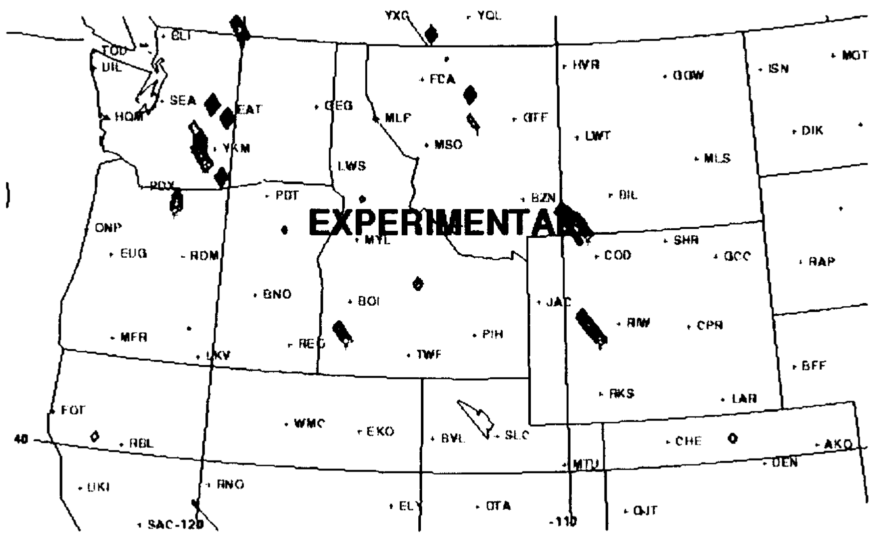
http://www.alaska.net/~nwsar/html/aawu/turb.html
Another chart from the Alaska Aviation Weather images, created by forecasters at the National Weather Service Forecast Office in Anchorage. These images are based on current satellite images, model data, observations, and forecaster knowledge of the local area.

Note that in addition to severity, coverage level is represented i.e., widespread, or isolated.



http://www.awc-kc.noaa.gov/awc/vvgraf/RUC_01_VVSTORM.GIF

The maps of VVSTORM are from the Rapid Update Cycle, Version 2 (RUC2). Displayed is the maximum vertical velocity *(not necessarily corresponding to hazard to aircraft)* in meters per second. The numbers are VVSTORM's maximum tops in kilofeet. The AWC computes grids of VVSTORM every hour. At times divisible by three (0000 UTC, 0300 UTC, etc.) the forecasts are out to twelve hours. At other times, the forecasts are only out to three hours. The displays for the "short" forecasts show the VVSTORM output from the previous "long" forecast at times past three hours.

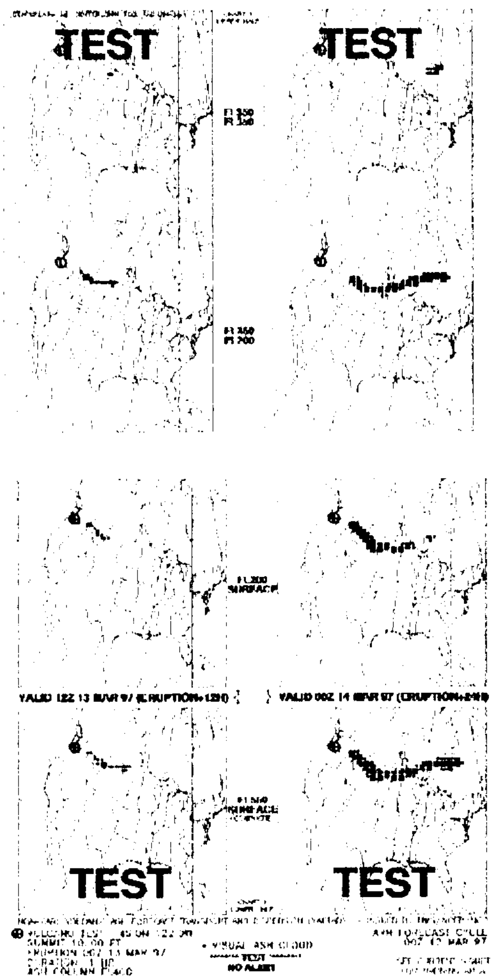


981202/0000V003 FL240-FL450 COMPOSITE RUC2 BREAKING PRESSURE DRAG (mb)

http://www.awc-kc.noaa.gov/awc/mwave/MWAVERUC21_03_NW_H.gif

MWAVE is a mountain wave diagnostic developed by the Experimental Forecast Facility (EFF) at the Aviation Weather Center. The important parameters are the vertical profiles of the wind speed (U) and the stability or temperature changes with height (N) and the height of the mountain (h) over which the air is flowing. MWAVE computes two diagnostics. First is the strength of the wave which MWAVE estimates as the drag the mountain wave exerts on the atmosphere. It is proportional to the product N*U*h, and units are in millibars. Second is the breaking potential which MWAVE estimates as a non-dimensional wave amplitude proportional to N*h/U. Mountain waves may be strong but non-breaking, as evidenced by an aircraft experiencing a smooth ride but significant up-and-downdrafts. They may also be breaking but weak with barely noticeable turbulence. The dangerous waves are strong and breaking. The maps of MWAVE you see are composites of breaking pressure drag in the labeled layers. Actual output to the AWC forecasters is in layers 1000-2000 ft thick. The areas are usually small because they are tied to they mountains that generate them. The EFF has thresholded the output into turbulence intensities:

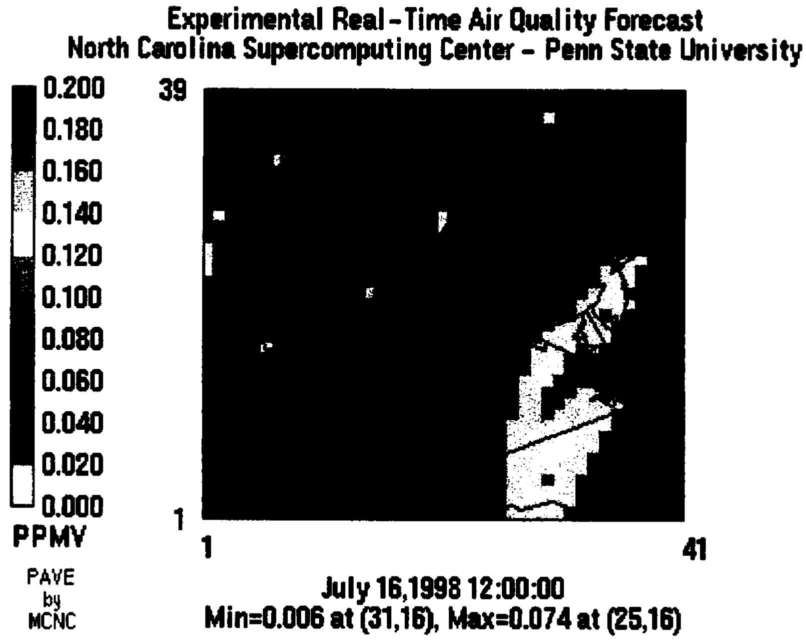
Breaking Pressure Drag	Turbulence Intensity
1 mb	Light Moderate
2 mb	Moderate
3 mb	Moderate Severe
5 mb	Severe



http://www.arl.noaa.gov/research/ep/vaftad.html

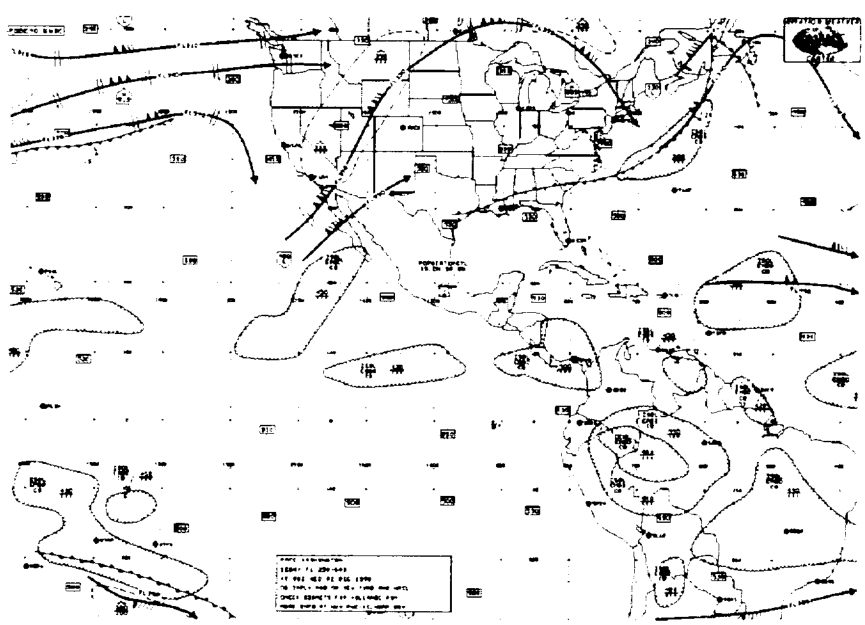
The NOAA Air Resources Laboratory (ARL) has developed the time dependent 3-dimensional Volcanic Ash Forecast Transport And Dispersion (VAFTAD) model for volcanic hazards alerts. An example 8-panel chart of the forecast visual ash cloud is shown at the end of the text. The four panels in any column are for a single valid time after eruption. Individual panels are for layers applicable to aviation operations and are identified at the side of a panel with upper and lower flight levels (FL) in hundreds of ft. The bottom panel is a composite layer, from the SURFACE to FL550, and is useful as an aid for issuing significant meteorological (SIGMET) advisories or for satellite imagery comparisons. For each column, the forecast valid time separates the upper three panels from the composite panel. Volcano eruption information is at the lower left. A description of the input meteorology and a message to "SEE CURRENT SIGMET FOR WARNING AREA" is at the lower right. The visual ash cloud symbol and run description are at the lower center. For runs other than ALERTS, the run description is also superimposed on the top and bottom panels of a chart (e.g. "TEST"). The example DIFAX output shown is valid for ERUPTION+12H (left column) and ERUPTION+24H (right column). Output chart is also available for +06H and +12H, for +18H and +24H, and for +36H and +48H. These charts, when placed in order, side by side, give an easy to visualize time dependent 3-dimensional view of the forecast volcanic ash cloud.

Predicted Ground-Level Ozone



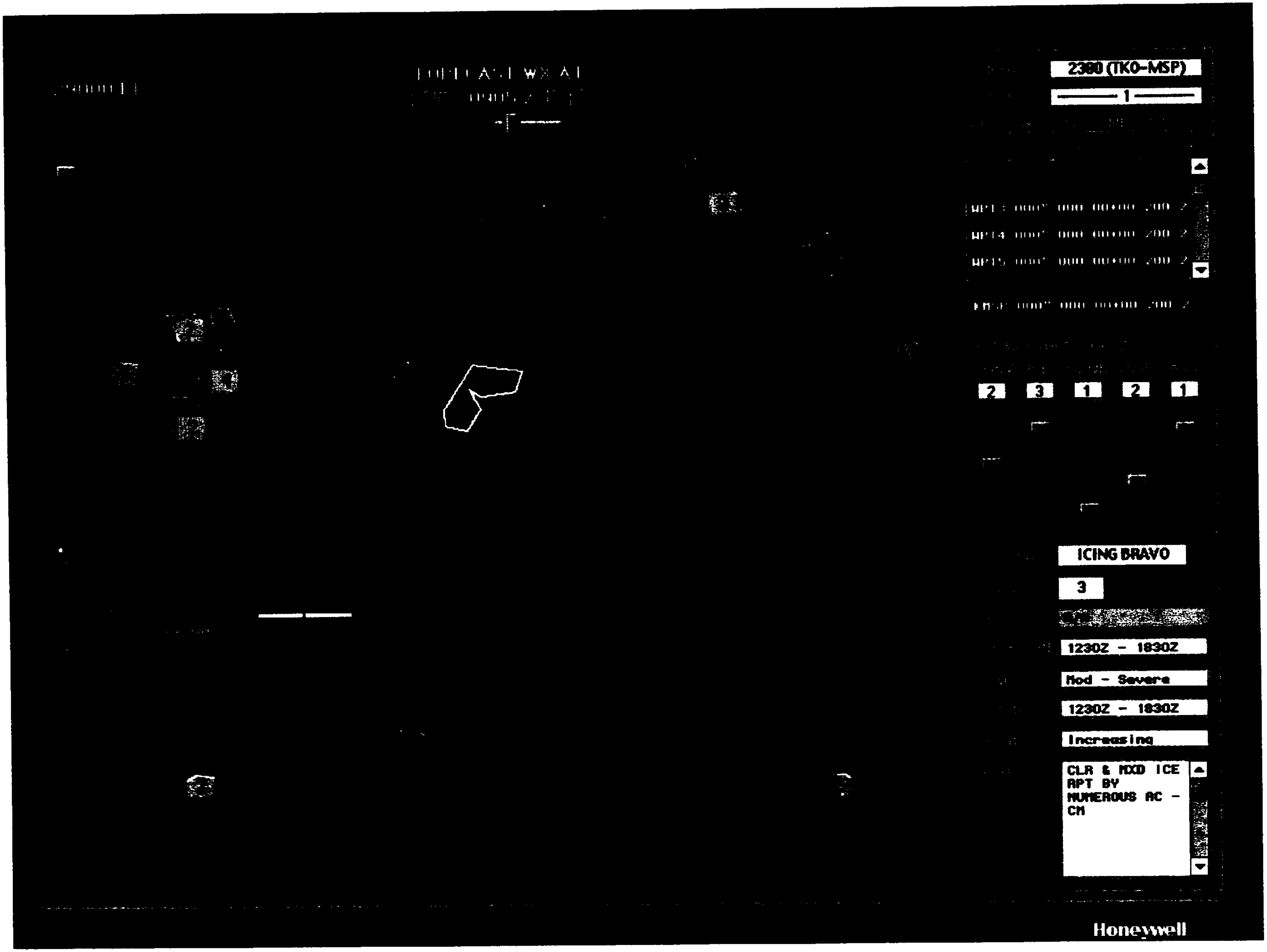
http://envpro.ncsc.org/NAQP/forecasts/archive/a19980715-d2.gif

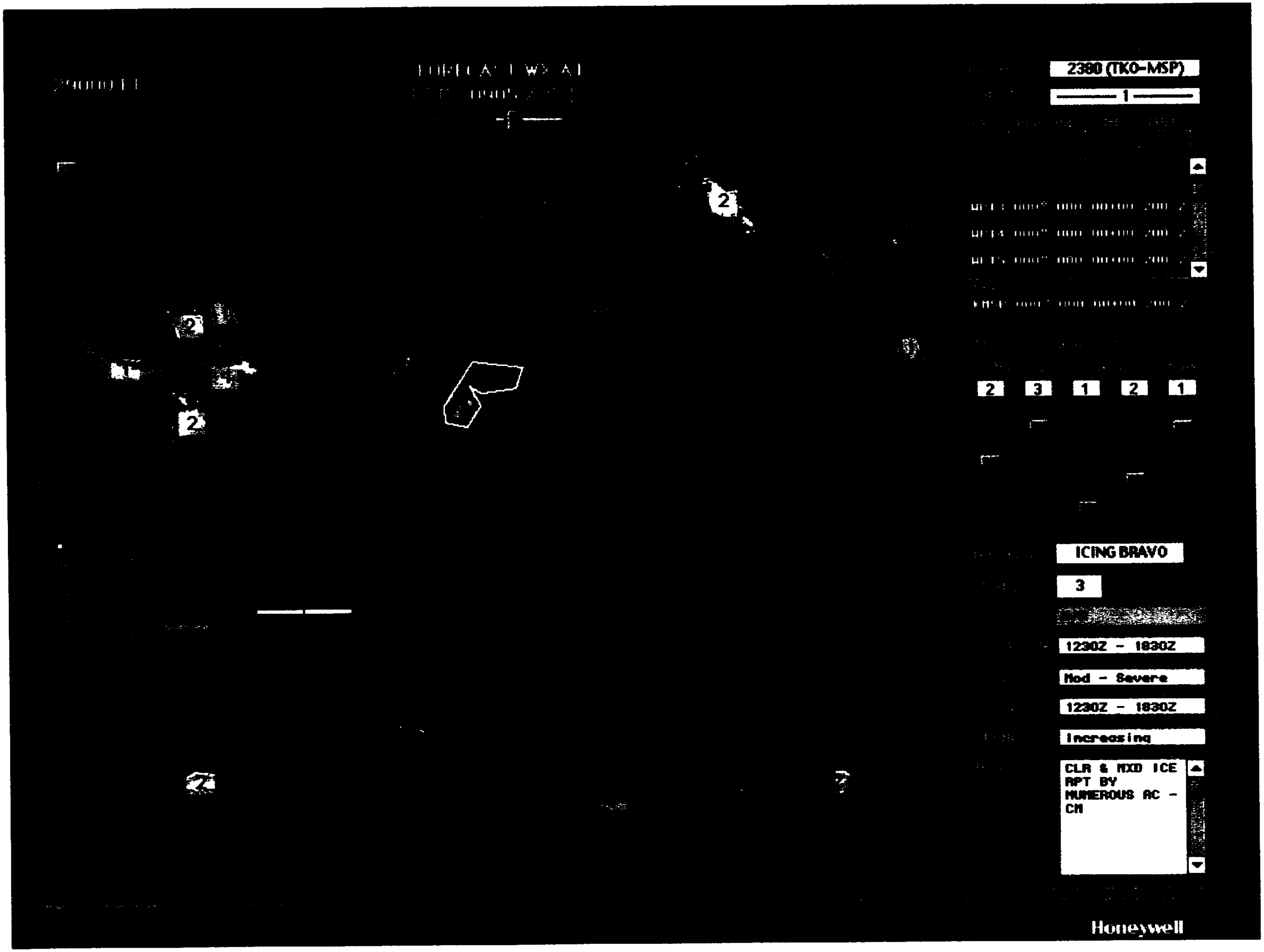
The Environmental Programs group at the North Carolina Supercomputing Center (NCSC) and the Penn State University Department of Meteorology are carrying out real-time simulations of meteorology, emissions and air quality to provide current day and next day forecasts of ground level ozone over portions of the eastern United States. We would be showing airborne levels of ozone though.



http://www.awc-kc.noaa.gov/awc/hilvl.html

Appendix F. Conceptual Display Layouts


2380 (TKO-MSP)
1
2
3
1
2
1
ICING BRAVO
3
1230Z - 1830Z
Mod - Severe
1230Z - 1830Z
Increasing
CLR & MXD ICE
RPT BY
NUMEROUS AC -
CM
Honeywell



2380 (TKO-MSP)
2 3 1 2 1
ICING BRAVO
3
1230Z - 1830Z
Mod - Severe
1230Z - 1830Z
Increasing
CLR & MXD ICE
RPT BY
NUMEROUS AC -
CM
Honeywell

References

Campbell, Ernest E., Recommended Flight-Crew Procedures if Volcanic Ash is Encountered, pp.151-156. http://www.geo.mtu.edu/department/classes/ge404/gcmayber/

Casadevall, T J, editor, Volcanic Ash and Aviation Safety: Proceedings of the First International Symposium on Volcanic Ash and Aviation Safety, U.S, Geological Survey Bulletin 2047.

Miller, Thomas P., "Volcanic Ash and Aircraft", U.S. Geological Circular - 1992 Yearbook Reports http://www.usgs.gov/reports/yearbooks/1992/geologic_volcanic.html

Schmid, Randolph E., "Volcanic Threat to Aviation Watched", Associated Press Wire Service, Aug 25 1995, AP-WS-08-25-95 1524EDT http://sddt.com/files/librarywire/DN95_08_25/DN95_08_25_13.html

Accident Synopsis ANC90FA020 "Scheduled 14 CFR 129 operation of KLM ROYAL DUTCH AIRLINES" National Transportation and Safety Board Report, Microfiche 41866A, Dec 1989. http://www.ntsb.gov/aviation/anc/90a020.htm

Accident Synopsis MIA96FA064 "Scheduled 14 CFR 121 operation of American Airlines, INC" National Transportation and Safety Board Report, Jan 1996.

Accident Synopsis DCA98MA045 "Scheduled 14 CFR 121 operation of AirTran Airlines, INC" National Transportation and Safety Board Report, May 1998.

Accident Synopsis LAX96LA013 "Scheduled 14 CFR 121 operation of UNITED AIRLINES, INC" National Transportation and Safety Board Report, Oct 1994.

Originals available at:
http://nasdac.faa.gov/asp/fw_ntsb.asp
http://www.ntsb.gov/NTSB/Query.htm
(Enter NTSB Identification # and year in search engine.)